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Vermiculite in the Stanleyville Area,

Eastern Ontario

Ontario Geological Survey
Mineral Deposits Circular 31

A. MacKinnon, P.W. Kingston and J.S. Springer

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Foreword

Since 1985, there has been a rapid growth in the market for exfoliated vermiculite, for use in the traditional applications in horticulture and loose-fill insulation, and as a replacement for asbestos in refractory and friction products.

Canada currently has no crude vermiculite production. Increasing concern with the presence of asbestiform minerals in vermiculite products from the United States, and with the possibility of interruption of supply from South Africa, has created new interest in the development of domestic sources of vermiculite. The most promising area for such development is in eastern Ontario, near Perth. The vermiculite occurrences of this area are located close to the major markets of southern Ontario, Quebec and the northeastern United States.

This report, in addition to providing information on the origin, physical properties, uses and world markets of vermiculite, presents the results of a comprehensive study of the occurrences in the Perth area. This study included detailed geological and mineralogical examinations and beneficiation tests of these occurrences. The results of this work indicate that under the present favourable market conditions, the Perth area occurrences have excellent potential for development as an Ontario source of vermiculite.

V.G. Milne

Director
Ontario Geological Survey

Abstract

Since the discovery of vermiculite at Stanleyville, near Perth, in 1950, numerous occurrences have been documented. The present investigation examined several of these occurrences—the Farrell, Pike Lake and Olympus Mines Ltd. properties—and found that at the Olympus Mines Ltd. property, mineralization consists predominantly of hydrobiotite rather than vermiculite as previous investigators have suggested; X-ray diffraction analysis supports this conclusion. Hydrobiotite is a layered mixture of biotite and vermiculite in some definite proportion, but is considered a vermiculite for commercial applications.

The Stanleyville–Pike Lake vermiculite occurrences appear to result primarily from hydrothermal processes; however, in the case of the Olympus Mines Ltd. property, supergene processes, i.e., weathering and alteration by circulating meteoric water, may also have influenced mineralization.

Separation and beneficiation studies conducted on chip and core samples, by the Canadian Centre for Mineral and Energy Technology (CANMET), has shown that ore behavior varies with depth; samples at depth were harder to crush and contained a higher proportion of brittle minerals, which resulted in the production of more fines. Favourable results were obtained using quiet-bubble flotation with a 10 percent hydrogen peroxide solution and tertiary amine as a collector; 95 to 98 percent hydrobiotite-vermiculite was recovered. After crushing, screening and exfoliation at 2000°F, 93 percent by volume hydrobiotite-vermiculite was separated by air tabling.

Tests performed on the dust fraction of the hydrobiotite-vermiculite ore found only a small concentration of fibrous minerals. The fibrous minerals consist of cylindrical fibres formed by the scrolling of altered flakes of vermiculite (12.1×10^8 fibres per gram, or 0.11 ppm mass concentration) and various amphiboles (1.32×10^8 fibres per gram). However, these do not appear to have characteristics that are of environmental concern, i.e., they are not asbestiform within the range considered to be hazardous.

This report includes a description of world resources, the vermiculite industry in Canada and the United States, and recent developments in processing and product applications.

Résumé

Depuis la découverte de vermiculite à Stanleyville près de Perth en 1950, de nombreux gîtes ont été documentés. Cette étude examine plusieurs de ces gîtes dont ceux de Farrell Lake, Pike Lake, et d'Olympus Mines Ltd.. Sur le gîte d'Olympus Mines Ltd., la minéralisation consiste surtout d'hydrobiotite plutôt que de vermiculite tel que suggéré auparavant; les analyses de diffraction aux rayons X confirment cette conclusion. L'hydrobiotite est un mélange de couches de biotite et de vermiculite selon des proportions bien définies, mais à des fins commerciales, l'hydrobiotite est considérée comme étant une vermiculite.

Les gîtes de vermiculite de Stanleyville-Pike Lake sont apparenment surtout le résultat de processus hydrothermaux. Dans le cas du gîte d'Olympus Mines Ltd., des processus supergènes, c'est à dire une altération crée par la circulation d'eaux météoriques, auraient pu également influencer la minéralisation.

Les études de séparation et de bonification réalisées à partir de fragments et de carottes de forage par le Centre canadien de la technologie des minéraux et de l'énergie (CANMET), ont montré que les caractéristiques du minerai varient selon la profondeur. Les échantillons prélevés en profondeur étaient plus difficiles à broyer et contenaient une plus grande proportion de minéraux cassants, ce qui a produit plus de particules fines. Des résultats satisfaisants ont été obtenus après flottation à bulles douces avec une solution contenant 10 % de péroxide d'hydrogène et de l'amine tertiaire comme collecteur. Selon ce procédé, 95 à 98 % d'hydrobiotite-vermiculite a été récupérée. Après broyage, tamisage et exfoliation à une température de 2000°F, 93 % par volume d'hydrobiotite-vermiculite fut séparée par table soufflante.

Les tests réalisés sur la fraction des poussières du minerai hydrobiotite-vermiculite ont indiqué seulement une faible concentration de minéraux fibreux. Les minéraux fibreux consistent de fibres cylindriques qui ont été formées par l'enroullement des feuillets altérés de vermiculite ($12{,}1 \times 10^6$ fibres par gramme, ou 0,11 ppm concentration de masse) et par diverses amphiboles ($1{,}32 \times 10^6$ fibres par gramme). Cependant ces fibres n'ont apparenment aucune des caractéristiques qui pourraient nuire à l'environnement, c'est à dire qu'elles ne sont pas asbestiformes selon les normes établies comme étant dangereuses.

Ce rapport comprend une description des ressources mondiales, de l'industrie de la vermiculite au Canada et aux États-Unis et des développement récents dans le domaine de la fabrication et des applications du produit.

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Vermiculite in the Stanleyville Area

Eastern Ontario

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Introduction

Several indicators suggest that a new producer of vermiculite might be successful on the world market. The four major sources, three in the United States and one in South Africa, together produce 93 percent of the vermiculite consumed by the western world (570 000 t in 1986). North America consumes over 60 percent of the western world production and since consumption within the United States balances production, the needs of Canadian industries (25 258 t in 1987) and those of the European block are largely dependent on imports from South Africa. Exfoliating plants across the western world are therefore vulnerable to interruptions of supply and to a price structure firmly controlled by the supplier. Against this background there is growth in traditional markets and a broadening range of uses for vermiculite.

The hydrobiotite-vermiculite occurrences of eastern Ontario, although extensively tested in the 1960s as aggregate for gypsum plaster, remain largely undeveloped. This project was initiated to investigate the occurrences in the Stanleyville–Pike Lake area, because good domestic market opportunities may now exist.

The initial phase of this study involved geologic mapping of the Stanleyville–Pike Lake area and of known vermiculite occurrences. Secondly, the Canadian Centre for Mineral and Energy Technology (CANMET) conducted separation and beneficiation tests on material from several prospects. In addition, this report provides a brief discussion of world resources, the United States and Canadian vermiculite industries and developments in processing and product application.

STUDY AREA

Field work for this study was centred at the hamlet of Stanleyville in North Burgess Township, about 11 km south-southwest of Perth (Figure 1). The Canadian Pacific Railways' main line passes through Perth. Pike Lake lies about 1 km west of the hamlet and extends some 6 km to the west, to just beyond the township boundary. Mapping was done over an area about 2.5 by 7 km; this block is oriented roughly parallel to Pike Lake and includes about half the length of the lake.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance and co-operation of R.K. Collings and J.M. Lamothe of CANMET, who undertook trial beneficiation of samples and provided information on previous testing; and of E.J. Chatfield of Chatfield Technical Consulting, Mississauga, who, in conjunction with the Ontario Research Foundation, tested samples for the presence of asbestiform fibres. N. Miles of Land Resources Research Centre, Agriculture Canada, located at the Central Experimental Farm, Ottawa, provided valuable mineralogical data. The authors wish to thank the Mineral Deposits Section, and in particular A.C. Colvine, of the Ontario Geological Survey, without whose support this project would not have been possible; and offer thanks to D.A. Williams and L.G. Thompson of the Ministry of Northern Development and Mines, Southeastern District, Southern Ontario Region, Ministry of Northern Development and Mines, for informative discussions.

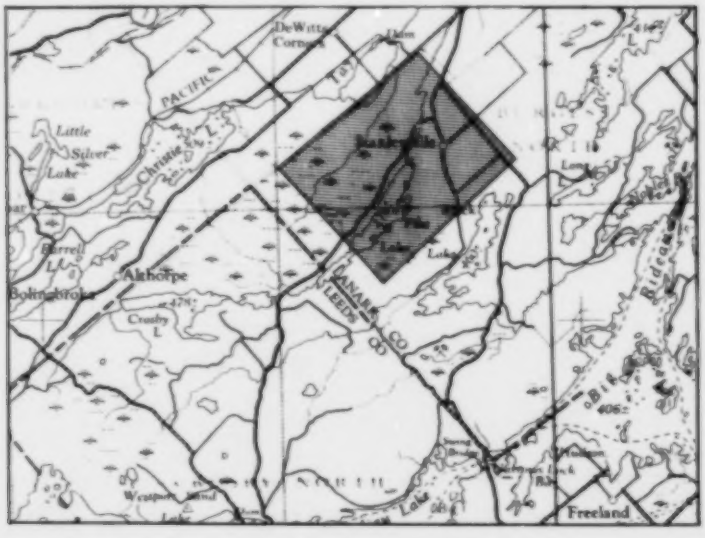

Figure 1. Key map, Stanleyville vermiculite area; scale, 1:50 000.

The authors gratefully acknowledge Cye Ross (Canalex Resources Ltd.) for information and access to his Olympus Mines Ltd. property.

Capable assistance was provided by W.M. Kelly, T. Mullings, R. Renouf, and J. Rudd.

This project was initiated under joint funding by the Resident Geologist's Office, Southeastern District, Southern Ontario Region and the Mineral Deposits Section, Ontario Geological Survey. The project was completed as part of the Canada–Ontario Mineral Development Agreement (COMDA), which is a subsidiary agreement to the Economic and Regional Development Agreement (ERDA) signed by the governments of Canada and Ontario.

World Vermiculite Production

In 1986, 93 percent of the world's vermiculite production (570 000 tons) was supplied by the United States and South Africa, with 56 percent and 37 percent, respectively (Meisinger 1987a). Figure 2 illustrates world production from 1940 through 1985. Other countries that presently produce vermiculite include Argentina, Brazil, Egypt, India, Japan, Kenya, Mexico and Tanzania; excluded from this list are countries with centrally planned economies.

World production capacity in 1984 was estimated at 650 000 short tons. The forecast for 1990 is 700 000 short tons, distributed as follows: the United States, 450 000 short tons; South Africa, 200 000 short tons; the rest of world, excluding countries with centrally planned economies, 50 000 short tons (Meisinger 1986a).

Most of the vermiculite from the United States is mined and beneficiated by W.R. Grace & Company, from mines at Libby, Montana and Enoree, South Carolina; several smaller independent producers also produce from mines near Enoree.

South African vermiculite is produced exclusively by the Palabora Mining Company Ltd. (PMC), a subsidiary of Rio Tinto Zinc Corporation, which operates mines at several locations in the Palabora Complex. Marketing is undertaken by two subsidiaries of Palabora Mining, American Vermiculite Corporation, of the USA, which sells into the Americas, and Mandoval Ltd., of the United Kingdom, with responsibility for the rest of the world, though principally Western Europe (Clarke 1981). South African vermiculite dominates European markets, and although its domestic markets are expanding, South Africa remains largely dependent on exports to support its production, some 167 287 t in 1985 (Morgan 1987).

Reserves and Resources

The United States reserves are mainly contained within one large deposit, located near Libby, Montana; the United States reserve base includes deposits in South Carolina, Virginia, North Carolina, Texas, Wyoming, Nevada and Colorado.

South African reserves are estimated to contain 80 percent of the rest of world reserves, excluding the centrally planned economy countries.

Table 1 lists the world vermiculite reserves and resources.

Vermiculite occurrences in Canada have been reported in British Columbia, and in Ontario, near Perth and Peterborough. Vermiculite associated with carbonatites has also been reported in northern Ontario, e.g., the Prairie Lake Carbonatite northwest of Marathon (Kretschmar 1984; Sage 1987).

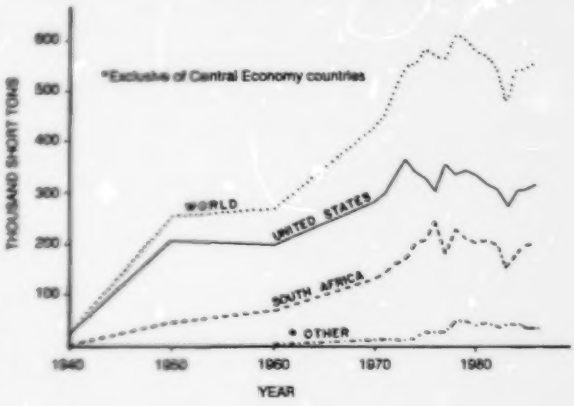

Figure 2. World production of vermiculite, 1940–1985.

Table 1. World vermiculite resources.

	Reserves	Other Resources[1]	Total Resources
North America (US)	100	25–100	large
South Africa	80	large	large
Rest of World[2]	20	large	large
Total	200	large	large

[1] *millions of short tons*
[2] *potential reserves*
[3] *does not include countries with centrally planned economies*
(after *Beauregard 1982; Meisinger 1986b, 1987b*).

Trends

Meisinger (1986a) states that "world reserves of vermiculite concentrate are more than adequate to meet estimated cumulative demand, 9.8 million tonnes (10.8 million tons) over the forecast period, 1983–2000." The demand for vermiculite is expected to increase at an average rate of two percent through 1990. Transportation costs will continue to limit the size of the market as well as vermiculite's competitive position with respect to other mineral commodities (Meisinger 1987b). However, recent concern in the United States over the presence of asbestiform minerals in some vermiculite products from the United States, and the gradual depletion of South African reserves, may eventually result in shortages worldwide.

THE UNITED STATES VERMICULITE INDUSTRY

Producers

The United States produced 287 600 t of vermiculite concentrates in 1986; domestic production was esti-

mated at 294 800 t in 1987 (Meisinger 1987a). Three companies produced the majority of the United States vermiculite, W.R. Grace & Company, Patterson Vermiculite Company and Strong-Lite Products Corporation (owned by Carolina Vermiculite Company Inc.); W.R. Grace is the largest of these and dominates US markets, both in terms of production and mineral exfoliation. W.R. Grace has a production capacity of 227 000 t from open pits at Enoree, South Carolina and Libby, Montana. Patterson Vermiculite Company and Carolina Vermiculite Company Inc. also operate mines at Enoree, South Carolina. Other small producers include: Micro-Lite Inc., Buffalo, Kansas; Virgina Vermiculite Ltd., Louisa, Virginia; Steetly Resources Inc., Millerville, Ohio; and Western Resources Company, Corvallis, Montana. Production is primarily consumed by domestic markets, with exports confined to Canada and Mexico. Exports to Canada, in 1986, were estimated to be 25 000 short tons, representing only eight percent of total sales (Meisinger 1986a, 1987a).

Vermiculite Exfoliating Plants

Exfoliated vermiculite, because of its low density and high volume, is expensive to transport. Therefore, crude vermiculite is beneficiated into well-defined grades and shipped to exfoliation plants serving specific geographical market areas. In 1986, crude vermiculite was exfoliated at 41 plants in 28 states (Meisinger 1987a); the majority of these, 29 plants in 24 states, were either operated by, or have licensing agreements with, the Zonolite Division of W.R. Grace & Company. More than half of the exfoliating plants in the United States are small, producing less than 4500 t per annum (Meisinger 1986a).

THE CANADIAN VERMICULITE INDUSTRY

The markets for crude, i.e., non-exfoliated, vermiculite are small and are restricted to a few special markets. In its expanded form, however, it has a wide range of applications and in the past 20 years the range of uses has increased markedly.

Canada has no crude vermiculite production; graded vermiculite is imported from the United States and South Africa. In 1987, Canada imported 25 258 t, valued at $4,202,955; imports from the United States totalled 20 859 t valued at $3,743,661, and from South Africa, 3340 t valued at $527,352 (Statistics Canada 1987). Imports, by province of clearance, for 1987 are listed in Table 2; it should be noted that the province of clearance does not necessarily represent the region of end use.

In 1987, 48.7 percent of the exfoliated vermiculite sold in Canada was used for horticulture applications, 38.7 percent for miscellaneous uses, and 12.6 percent for loose-fill insulation . However, there may be a greater proportion used for loose-fill insulation than statistics indicate (Oliver Vagt, Energy Mines and Resources Canada, personal communication, 1989). Figure 3 illustrates trends in consumption of exfoliated vermiculite in Canada from 1968 through 1987. Since 1985 there has been a marked increase, from 11.8 to 38.7 percent, in miscellaneous uses of vermiculite. This is probably due largely to the use of vermiculite as an asbestos replacement in refractory and friction product applications.

Markets exist for approximately 24 500 to 29 000 t/year of vermiculite concentrates, and 7300 t/year of expanded vermiculite, for a favourably located Ontario deposit, such as at Perth, because of the high transportation costs of importing vermiculite (Beauregard 1982).

Table 2. The Canadian vermiculite industry.

	tonnes	Value
Nfld.	280	$28 550
N.S.	363	$50 811
Que.	8 304	$1 315 085
Ont.	9 124	$1 598 912
Man.	1 409	$259 827
Alta.	2 546	$442 849
B.C.	3 232	$506 971
TOTAL	25 258	$4 202 955

from Statistics Canada (written communication, 1988).

Vermiculite Exfoliating Plants

Canada has seven vermiculite exfoliating plants. Two are located in each of Ontario and Quebec, with one in each of Manitoba, Alberta and Nova Scotia. These exfoliation plants are listed in Table 3.

In Canada, as in the United States, most exfoliating plants are tied to the major producer, W.R. Grace and Company Ltd., either through ownership or licencing agreements. Beauregard (1982) reports that "a somewhat less stringent agreement exists between Palabora Mining, the South African producer, and Vermiculite Insulating[1], which allows the company to purchase from W.R. Grace occasionally."

[1] *Vermiculite Insulating Limited, Lachine, Québec and Rexdale, Ontario.*

Table 3. The principle vermiculite exfoliating plants in Canada.

Operating Company	Province	City
V.I.L. Vermiculite Inc.	Quebec	Lachine
Domtar Inc.	Quebec	Montreal
W.R. Grace & Co. of Canada Ltd.	Ontario	Ajax
	Ontario	St. Thomas
	Manitoba	Winnipeg
	Alberta	Edmonton
Annapolis Valley Peat Moss Co. Inc.	Nova Scotia	Berwick

from Vagt (1988).

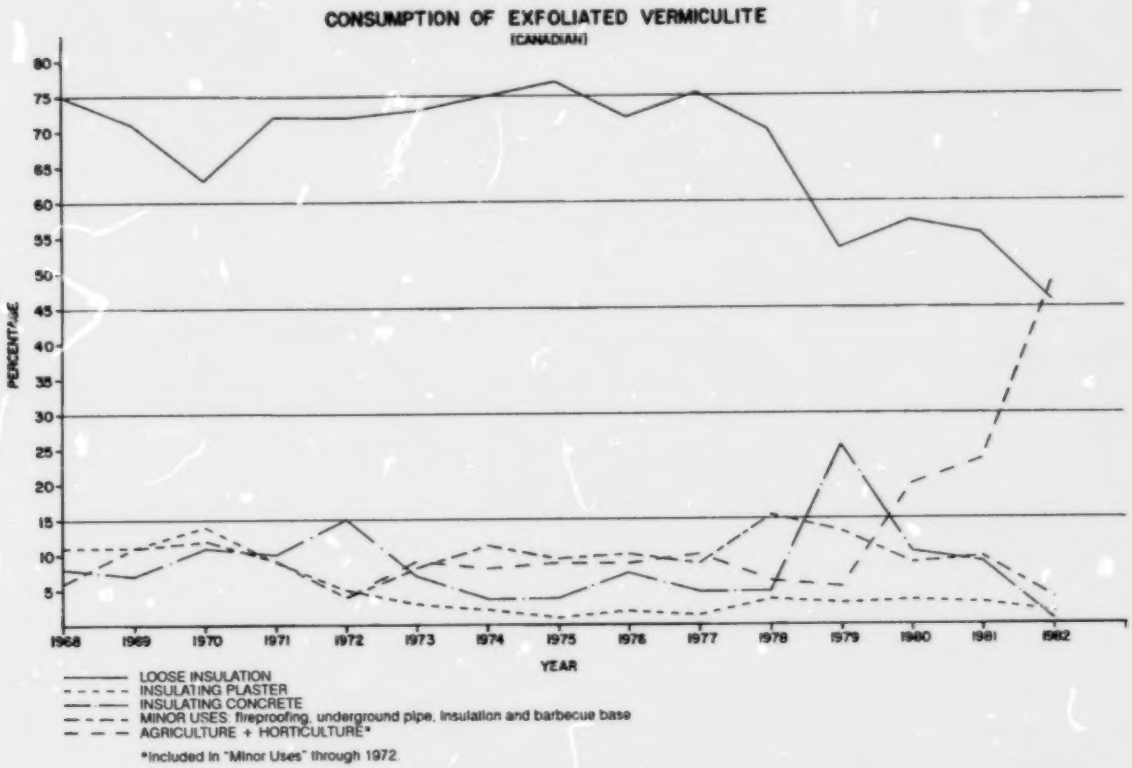

Figure 3. Canadian consumption of exfoliated vermiculite, 1968–1987 (data from Energy, Mines and Resources Canada (1970–1988)).

Comparative Transportation

As is the case with many industrial minerals, vermiculite is very sensitive to transportation costs.

In 1986, the average value for exfoliated vermiculite sold and used in the USA was US$210.00 per short ton, free on board (FOB) the exfoliating plant (Meisinger 1987a).

Beauregard (1982) estimated prices for crude vermiculite landed at major ports as listed below:

Source	Destination	Cost[1]
Libby crude	Montreal	$160 to $220
	Toronto	$152 to $212
South African crude (micron quality)	Montreal	$190

[1]*FOB per short ton*

To assess the competitiveness of one of Ontario's more promising deposits, Beauregard (1982) costed transportation by various means from Libby, Montana and from Perth, Ontario to various exfoliating plants around the Great Lakes, both in the United States and Canada. It is apparent that for 60 percent of the destinations studied, a product of comparable FOB cost could be delivered more cheaply from Perth.

Using trucking as the chosen transportation method, Beauregard (1982) estimated delivery to Montreal from Perth at $28 to $40 per short ton, compared to $75 to $80 per short ton from Libby, Montana. Transportation from Palabora, South Africa, to Montreal at that time was estimated to cost $101 per short ton.

Conversely, shipping Ontario vermiculite from Perth via Montreal to Rotterdam or Antwerp was calculated at less than $80 per short ton, a price that could compete with the cost of transportation of South African vermiculite. For Montreal to the UK, transportation was reckoned at $73 to $79 per short ton (Beauregard 1982). Table 4 contains data on tarrifs governing vermiculite shipping.

Table 4. Tarrifs, 1988.

Non-Exfoliated		
No. 2530.10.10	Duty Free	
Exfoliated		
No. 6806.20.00	Canada	United States
Most favoured nation	10.2%	4.9%
General preferenial	6.5%	Free

from Statistics Canada (written communication, 1988).

Recent Posted Prices

The price quotations in Table 5 are taken from *Industrial Mineral Magazine*, December, 1988, and it should be

Table 5. Prices, 1988.

South African, bulk, short ton, FOB Rotterdam	US$115.00 to US$178.00
Raw, FOB USA plant, bulk, sh. tons	US$65.00 to US$135.50
South African, crude bulk FOB barge, Gulf coast, sh. tons	US$105.00 to US$170.00

from Anonymous (1988).

noted that price will vary according to type, source, quality, quantity and application of the vermiculite.

Economic and Quality Criteria for a Successful Canadian Deposit

Any Canadian deposit expected to compete with the US or South African ores would need to:

- grade more than 30 percent vermiculite, although deposits of exceptional quality can be profitable at 20 percent
- contain no more than 10 percent other micaceous material, e.g., biotite or phlogopite, to simplify separation
- be large enough to mine by open pit methods at a rate of 30 000 to 50 000 short tons per year, a tonnage which would cover the market in Canada and some of the market in the adjacent USA.
- contain predominantly large-flake vermiculite, as small-flake markets are already well-supplied
- be located as close to user markets as possible

The material itself must:

- have a bulk density of 4 to 10 pounds per cubic foot (0.064 to 0.160 g/cm^3) after exfoliation
- yield an expansion product that is not brittle and does not decrepitate during exfoliation
- have a sufficiently high absorptive property for use in horticulture
- become a product which is very pale in colour
- use as little energy for exfoliation as do existing crude vermiculites
- contain minimal amounts of fibrous or dusty materials in order to reduce possible health hazards

Provenance and Applications

PROPERTIES OF VERMICULITE

Commercial vermiculite refers to a family of monoclinic, hydrated, ferromagnesian aluminosilicate minerals of secondary origin, with the ability to exfoliate upon rapid heating (Wilson 1981). Low density, chemical inertness, high fluid absorbability, high cation-exchange capacity, resistance to fire, and good thermal and acoustic insulation qualities are among the desirable properties of vermiculite that are utilized by a wide variety of industries such as construction, engineering, metallurgy, horticulture and agriculture.

The variations in chemical composition, colour and physical properties of vermiculite are partially due to the progressive nature of the metamorphic reactions by which it is formed. At Stanleyville, this fact was evident in the field and in thin sections, and is reflected in the behaviour of various samples upon processing. The colour ranges from shades of brown, red-brown and green to almost black, with true vermiculite being a light silvery or golden tan colour. The lighter coloured varieties seem to be more highly hydrated. Flakes are inelastic and usually warped or bloated in appearance, with hardness ranging from 1.5 in true vermiculite to between 2.5 and 3 in unaltered mica, using the Mohs scale. The expanded product is very light, with densities between 5 and 10 pounds per cubic foot (Bush 1976). Commonly, exfoliation values are between 8 and 15 times but ideally may reach a maximum of 30 times (Deer et al. 1980). Exfoliation values are explained by Strand and Steward (1983):

> When heated quickly to elevated temperatures, vermiculite expands by exfoliation at right angles to the cleavage into worm-like particles...This characteristic of expansion is the result of the mechanical separation of the layers by the rapid conversion of contained water to steam.

The amount by which individual flakes may expand relative to the original thickness is termed the "exfoliation value".

Since vermiculite is seldom used in the unexfoliated form, typical physical and chemical properties of exfoliated vermiculite are listed in Table 6 (Anonymous 1977; Roskill Information Services 1986).

Table 6. Typical physical properties of exfoliated vermiculite (SI units).

Loose bulk density (crude)	640–960 kg/m^3
Loose bulk density (exfoliated)	56–192 kg/m^3
Sintering temperature	approx. 1260°C
Melting point	approx. 1315°C
Specific heat	840 j/kg°C
Specific gravity	2.6
Thermal diffusivity	23.226 cm^2/hr
Thermal conductivity	0.062–0.065 W/m^2°C
Specific heat at 32°C (0°F)	0.20 Cal/gm/°C
Specific heat at 572°C (300°F)	0.24 Cal/gm/°C
Cation exchange capacity	
vermiculite ore (S. Caroline)	70 milli-equivalents/100 g
vermiculite ore (Montana)	35 milli-equivalents/100 g
exfoliated vermiculite (S. Carolina)	20–60 milli-equivalents/100 g
exfoliated vermiculite (Montana)	20–30 milli-equivalents/100 g

ORIGIN OF VERMICULITE

Considerable controversy has arisen, through the years, over the origin of vermiculite. Circulating meteoric waters and hydrothermal alteration, either acting independently or together, are the predominant formational processes suggested for the genesis of vermiculite. The formational process is important to the economic potential of a deposit since vermiculite formed by meteoric water would be confined to the shallow zone of circulation, where as vermiculite of hydrothermal origin may reasonably be expected to continue to depth.

The pyroxenite-hosted deposit at Libby, Montana, leaves little doubt as to its hydrothermal origin, with vermiculitization of the biotite occurring to a depth of a 1000 feet or more (Harben and Bates 1984). Both theories have been suggested for the vermiculite at Palabora, South Africa, but a meteoric origin was finally accepted since the vermiculite gradually grades into unaltered phlogopite at depths of 120 to 150 feet. The deposit at Enoree, South Carolina is an example of vermiculite formed by both processes (Wilson 1981).

Barshad (1948) and Hoadley (1960) describe the process of vermiculitization as follows:

> Alteration of mica to vermiculite is accomplished by a slight re-arrangement of the atoms within the lattice layers and by replacement of the interlayered K^+ ions by other cations, generally Mg^{2+}, or Mg^{2+} plus Ca^{2+} ions in natural vermiculite, by means of base exchange. This exchange process is accomplished by the introduction of varying amounts of water molecules between the lattice layers, the amounts being determined in any one case by the kind of exchangeable ion present. Oxidation of Fe^{2+} to Fe^{3+} accompanies hydration, with partial replacement of Si^{4+} in the silicon-oxygen tetrahedron.

Oxidation is marked by a colour change from brown to red, as fine-grained hematite precipitates in the space between the double layers in the mica sheet.

At Stanleyville, this feature was observed on the Farrell property, and at numerous other localities, by Hoadley (1960), Guillet (1962) and the present authors. Locally, light to dark green vermiculite was observed, either alone or intermixed with the hematitic variety. The colour variation may reflect fluctuations of the water table, with oxidizing conditions producing a red colouration and reducing, a greenish. Hoadley (1960) observed progressive changes from brown to green in one specimen, indicating the green colouration developed after hydration of the phlogopite.

Three general groups of rocks in the study area play a significant role in the development of vermiculite. This is best seen in a mineralized zone on the Olympus Mines Ltd. property. The units are 1) Grenville Supergroup metasedimentary rocks, 2) Late Precambrian intrusive rocks, and 3) Paleozoic rocks.

The host for hydrobiotite-vermiculite mineralization was probably originally a phlogopite-rich dolomitic marble, which is seen throughout the study area but especially at the Farrell property. Late Precambrian acidic intrusions migmatized the country rock and produced hydrothermal solutions which altered the marble to pyroxenite, in the case of the Olympus Mines Ltd. property. Recrystalization, due to the addition of silica either as SiO_2 or as silicates, may have increased brittleness, and hence permeability, facilitating the circulation of the hydrothermal fluids. Alternatively, close proximity to the Middle Ordovician erosion surface may have influenced mineralization with the permeable zone acting as a conduit for later fluid movement (J. Springer, Ontario Geological Survey, personal communication, 1989).

The degree to which each of these processes influenced mineralization is presently uncertain. However, the coexistence of phlogopite, hydrobiotite, smectite, corrensite and chlorite, as observed in samples from the Olympus Mines Ltd. property, is representative of various stages of the transformation sequence of the anhydrous mineral (phlogopite) to hydrous ones (N. Miles, Agriculture Canada, personal communication, 1989). De Kimpe and Miles (1988) state that the formation of corrensite at the expense of phlogopite implies 1) loss of inter-layer K+ from phlogopite, 2) formation of an expanding mineral with hydrated interlayer cations, and 3) chloritization of alternate layers of the expanding mineral. Therefore, the presence of corrensite and allietite (talc-smectite) as the major clay-sized constiuent implies further alteration of the Olympus ore to these phyllosilicates (Miles and Springer 1989). The presence of allietite in the highly altered saprolitic zone near surface suggests further supergene alteration due to weathering.

De Kimpe and Miles (1988) explain:

> The co-existence of vermiculite, smectite and chlorite along with corrensite and phlogopite is representative of various stages of the transformation sequence of the anhydrous minerals to hydrated ones. The conditions of formation are incompatible with the range of temperature and pressure associated with the metamorphism in the area and strongly suggest that formation of corrensite occurred during a later stage of hydrothermal activity.

In a pit at the Pike Lake occurrence, on Concession 9, Lot 17, North Burgess Township, vermiculitization was noted 4 to 5 m below the surface of a phlogopite body, immediately adjacent to a syenitic feldspathic stringer. Completely unaltered phlogopite occurs about a metre on either side of the stringer and immediately below the soil cover, leaving little doubt as to a hydrothermal origin for the vermiculite. Corrensite occurs in a nearby roadcut on Hwy. 10, where it was formed at the expense of phlogopite by hydrothermal alteration (Miles and De Kimpe 1988). De Kimpe and Miles (1988) state that corrensite is frequently formed in the dolomitic marbles of southeastern Ontario by hydrothermal alteration of phlogopite.

The Paleozoic rocks, although not genetically important to the mineralized process, are still an essential component in development of vermiculite in southeastern Ontario. These thin units capped and preserved the soft, altered pyroxenite bodies until the waning phase of glaciation scraped off the remnants of Paleozoic cover, exposing the pyroxenite to surficial weathering.

VERMICULITE USES

Vermiculite is largely used in the exfoliated form; primary markets are the construction industry where it is used in ultra-lightweight aggregates, and the horticultural industry in which it is used for fertilizer and litter. The demand for crude vermiculite (non-exfoliated) is very limited, as uses are restricted to a few specific applications, such as, fillers in fire-resistant wallboard, loose-fill cover over molten metal, slag coagulant, and oil-well drilling (Beauregard 1982; Power 1986).

Marketing of exfoliated vermiculite in well-defined grades has proven to be useful in construction, agriculture and other industries. Generally, the large-flake grades are used in loose-fill insulation, the medium-flake, for various bonded aggregates and the fine-flake vermiculite for chemical and agricultural carriers, in refractory products, and as a filler and/or extender in paints, plastics and rubber (Beauregard 1982; Power 1986). Vermiculite is used in construction materials where lightweight, thermal insulation and acoustic qualities are of particular importance, such as for roof decks.

Exfoliated vermiculite serves a wide variety of applications; those listed below are from W.R. Grace and Company (1971).

Construction:

- gypsum plaster fireproofing
- concrete fireproofing
- cold storage insulation
- loose fill insulation
- masonry wall insulation
- underground pipe insulation
- sound conditioning
- preformed concrete roof tiles
- insulating concrete roof decks and floors

Agriculture:

- mulch
- fertilizer conditioners
- anticaking agent for fertilizers
- hatchery litter
- poultry litter
- soil conditioners
- cutting beds
- propagation of seed
- encapsulation of seeds
- plant nutrients
- carriers of insecticides, herbicides, fungicides, fumigants
- soil modification, i.e., bulking agent

Metallurgy:

carrier for additives
lubricant for extrusion and drawing
mould linings
insulation over molten zinc and lead

Chemistry:

protective coatings
molecular sieves
absorbent
carrier
diluent
cryogenics

Ceramics:

castable insulation
insulating fire brick
building blocks
prefabricated chimneys

General:

packing material
disposal of nuclear wastes
transportation of hot ingots
insulation of liquid air storage vessels
insulation of household appliances
fillers in paints, plastics and rubber

Vermiculite cement compounds are used as an incombustible sealant in mines; sprayed on, it adheres to most substrates. It is particularly useful as a fire retardant coating on structural steelwork in oil refineries and chemical plants (Mandoval Ltd. 1972).

Specifications for Crude Vermiculite

There are as yet no Canadian Standards Association (CSA) specifications for the lightweight aggregates. Production and application are based on the following American Society for Testing and Materials (ASTM) designations (Vagt 1988):

C 330-75a Lightweight Aggregates for Structural Concrete

C 331-69 Lightweight Aggregates for Concrete Masonry Units

C 332-66 Lightweight Aggregates for Insulating Concrete

W.R. Grace & Company grades domestic vermiculite on the basis of bulk density and size.

The grading system for South African (Palabora) vermiculite, in accordance with recommendations by the International System of units, is based on the metric system.

The particle size used by Palabora Mining Company Ltd. is coarser than that used by W.R. Grace & Company; Palabora measures grades with maximum sizes on the square, whereas W.R. Grace measures the diagonal.

Table 7. Size classification of USA crude vermiculite.

W.R. Grace designation	Tyler Mesh	Approx. equivalent max. size (inches)	Density (lb/cu ft)
1	3–10	1/4	4 to 7
2	8–14	3/32	4 to 8
3	10–35	1/16	5 to 9
4	28–65	1/32	6 to 10
5	35+	1/64	8 to 11

after *Anonymous (1977); Meisinger (1980).*

Table 8. Size classification of South African crude vermiculite.

Palabora designation	Old grade number	Size range (mm)	wt% passing 150 seive
Premium	6	−16 + 8	90 to 100
Large	4	−8 + 4	90 to 100
Medium	3	−4 + 2	90 to 100
Fine	2	−2 + 1	90 to 100
Superfine	1	−1 + 0.5	80 to 100
Micron	0	−0.5 + 0.25	50 to 100

after *Clarke (1981).*

Table 9. Typical chemical analyses of commercial vermiculite.

	Libby Montana (%)	Encoree S. Carolina (%)	Palabora South Africa (%)
SiO_2	38.64	38.66	39.37
MgO	22.68	20.04	23.37
Al_2O_3	14.94	17.36	12.08
Fe_2O_3 (Total Fe)	9.29	8.45	5.45
Na_2O			.80
K_2O	7.84	5.24	2.46
BaO			0.03
CaO	1.23	0.75	1.46
Li_2O			0.03
Cr_2O_3	0.29	0.50	nil
MnO	0.11	0.12	0.30
P_2O_5	trace	trace	0.15
TiO_2			1.25
S	trace	trace	0.18
F			0.25
Cl	0.28	0.52	0.02
CO_2			0.60
H_2O	5.29	8.71	
Loss on ignition at 850°C			14.24
TOTAL	100.59	100.36	102.04

after *Myers (1960), Anonymous (1977).*

SUBSTITUTE MATERIAL

Expanded perlite and exfoliated vermiculite both benefit from a very low bulk density and are therefore able to substitute for each other in most applications. The choice of one mineral over the other, apart from price, is often the source of supply. Here, perlite has an added advantage with its wide geographic production base in North and Central America, the Mediterranean, Eastern Europe and the Pacific Rim, while vermiculites production is primarily restricted to South Africa and the United States. Perlite is slightly cheaper, and therefore, generally favoured in most construction materials applications. Perlite has captured much of the lightweight aggregate markets in the United States and Europe (Power 1986).

In plasters, a traditionally vermiculite market, perlite is now favoured, particularly where light weight and good plastering properties are required. However, ver-

Table 10. Specifications for USA exfoliated vermiculite.

	USA Expanded Vermiculite				
Grade	Sieve size	Cumulative % retained		Bulk Density (ASTM C-29)	
No.*	USA	Max	Min	lb./cu.ft.	End Uses
1	3/8	10	0	4 to 7	loose-fill house insulation.
	4	60	30		
	8	95	65		
	16	100	85		
2	4	5	0	4 to 8	loose-fill refrigerator insulation, concrete aggregate.
	8	80	20		
	16	99	75		
	30	100	90		
3	8	10	0	5 to 9	plaster aggregate.
	16	60	20		
	30	95	65		
	50	98	75		
	100	100	90		
4	16	5	0	6 to 10	filler, insecticide, carrier, extender for paint.
	30	65	15		
	50	98	60		
	100	100	90		

* *Grades 1, 2 and 3 all find applications in agriculture;* from *Anonymous (1977).*

Table 11. Specifications for South Africa expanded vermiculite.

Grade	Old Number	Size (mm)	Density (lb./cu.ft.)	End Uses
Premium	6	16 down	3.5 to 4.5	loose-fill house insulation
Large	4	8 down	4.0 to 5.0	insulation
Medium	3	4 down	4.5 to 5.5	concrete aggregate
Fine	2	2 down	5.5 to 7.0	plaster aggregate
Superfine	1	1 down	6.5 to 9.0	rooting medium for tobacco seedlings
Micron	0	0.5 down	6.5 to 10.0	

from *Anonymous (1977).*

miculite is preferred where fire-proofing or increased adhesion is desired (e.g., spraying on mine walls as a sealant and fireproofing medium). Other, more dense but less costly, substitutes in concrete and plaster include expanded clay, shale, slate or slag.

Vermiculite's fire-retardancy characteristics are utilized by the refractories industry, in which vermiculite and selected binders are compressed and formed into blocks, boards or specialty shapes for use as "back up" or hot-face applications in the temperature range 1100 to 1200°C. While the majority of vermiculite is used in these preformed products, it is also the principal lightweight aggregate in refractory concretes such as castables and ramming mixes (Power 1986). Vermiculite is finding greater acceptance as an asbestos alternative in many refractory and friction applications.

Power (1986) states:

> While vermiculite excels in the high temperature applications, perlite is the preferred medium for use at the other end of the temperature spectrum. Perlite insulation is particularly important in the cryogenic insulation of gas storage tanks and sea going vessels where gases such as oxygen, nitrogen, methane, propane, ethylene and ammonia have to be kept in a liquid state at extremely low temperatures.

Perlite is preferred because of its low moisture retention compared to vermiculite, since any uptake of moisture increases thermal conductivity and significantly reduces the insulation properties of a given material. Although perlite is preferred over vermiculite in this particular application, it should be noted that rock wool and plastic foams are becoming increasingly more competitive in these applications.

It is in the insulation industry, that vermiculite has experienced its most significant set backs. Here vermiculite has had to compete with numerous cheaper materials, such as, mineral wools, polystyrene foam, polyurethane foam, wood fibre, milled newsprint or wood pulp treated with fire resistant chemicals, perlite and glass fibre.

In horticulture, vermiculite's property of cation exchange, and perlite's inherent porosity, has resulted in a complementary relationship between the two minerals. As a result, the mineral selected depends on the degree

of water retention, nutrient induction, soil porosity and root anchorage required. Other substitutes used in horticulture include peat, sawdust, bark and other plant materials, and synthetic soil conditioners.

Other applications in which vermiculite and perlite compete include: fillers in paints and plastics, abrasives, oil absorbers and animal feed additives.

RECENT DEVELOPMENTS

In recent years, the market for fire retardant boards and panels has experienced significant growth. These products are manufactured by a variety of techniques. In one method, similar to that employed for wood chipboard, exfoliated vermiculite and inorganic and/or organic binders are mixed, then compressed into the required shape and cured. This type of material is used for ceiling tiles, building and marine panels, fire protection cladding and high temperature insulation boards. An alternative method uses a wet slurry of exfoliated vermiculite blended with calcium silicate binders and other additives. "The slurry is subsequently dewatered and cured by the Fourdrinier/Magnani process for making wood fibre and asbestos boards etc. ..." (Clarke 1984; Dickson 1982).

The Torbed process is a recent technological advancement in thermal processing, developed by Torftech Ltd. of the UK, which if proven to be cheaper or more efficient than existing processes, may convert some presently uneconomical vermiculite deposits into a viable ore. The process resembles no existing single process but incorporates three established techniques in combination—hovercraft, fluidized bed and cyclone technologies (Clarke 1984; Dodson 1986).

Figure 4 illustrates the Torbed toroidal fluidized bed furnace. Clarke (1984) cites a number of advantages to this furnace:

- High rates of energy transfer that minimize processing time
- Rapid loading and unloading of material, enabling a continuous, automated batch process
- Low fluid-pressure drop across the bed, allowing for treatment of gas, heat recovery and other high-volume gas treatment processes
- Close control of temperature
- Compactness of design
- Amenability to control by an easily installed microprocessor

The method is compact, mobile and energy efficient.

New applications are especially important to the Stanleyville area, as this vermiculite is overly friable for most current uses. Products currently the subject of experimentation are vermiculite-based paper, fabrics, foams and silicon-based products.

D. Ballard of Imperial Chemical Industries' (ICI) PLC Research Laboratories in the UK, has conducted research into silicon-based vermiculite products. One of these products, which mimics plastic, may be an effective substitute for asbestos. Potential applications include fire-resistant facings for organic foams, wall paper and roofing installations, high-temperature gaskets and expansion joints in furnaces and boilers, heat resistant interlayers in domestic appliances and wrapping for electrical cables in control systems of chemical plants (*The Globe and Mail*, March 30, 1984).

The conversion of vermiculite to a usable product is accomplished through the following series of steps. The ore is first refluxed for approximately 30 minutes in a saturated solution of sodium chloride in which the divalent magnesium ions are replaced by monovalent sodium ions. The leached magnesium ions and excess sodium chloride are washed away. A further refluxing by 2M N-butylammonium chloride for 30 minutes, results in monovalent butylammonium ions substituting for the sodium ions. The excess ions are again washed away. During this second washing the vermiculite becomes hydrated and expands up to 30 times, producing a water-based gel in which the interlayer spaces of the mineral are filled with water. Refluxing with sodium chloride is not essential but greatly reduces processing time (Ballard and Rideal 1983). The gel is then sliced into a "soup" of thin plates, each 5 to 20 μm thick. These plates are so flexible that they will wrap around fibres dipped into the "soup" (*The Globe and Mail*, March 30, 1984). The coatings are stabilized during the final stages of drying by exchanging N-butylammonium ions with NH_4^{+1}, or any multivalent ion, e.g., Mg^{2+}, Ca^{2+}, Zn^{2+} (Ballard and Rideal 1983).

Vermiculite films can be formed around fibres or on metal surfaces; some films are more resilient than films obtained from organic polymers such as polyethylene and polyethylene teraphthalate (PET).

ICI has extended glass fibre into applications which previously required the use of asbestos-containing materials or of costly silica or ceramic fibre products; applications such as vermiculite coated glass fibre papers and textiles. Automatic machinery coats or impregnates the fabric with vermiculite which is dispersed in a slurry (ICI pamphlet, Fortress 'T', ICI (1984)).

ICI has demonstrated the ability of these coatings to act as a thermal barrier. For example, uncoated glass fibre possessed a maximum operating temperature of 550°C, however when a vermiculite coating was applied, the globules were retained and prevented from flowing even when the glass was completely melted in a furnace at 1200°C. Coatings on aluminum foil, similarly, prevented melting when subjected to high temperatures (Ballard and Rideal 1983). Materials coated with the films are virtually flame proof because heat is conducted away along the coating layers seven times faster than through the layers (*The Globe and Mail*, March 30, 1984). These properties suggest that vermiculite may be a preferrable and economically viable alternative to asbestos (for some applications), without the associated health hazards.

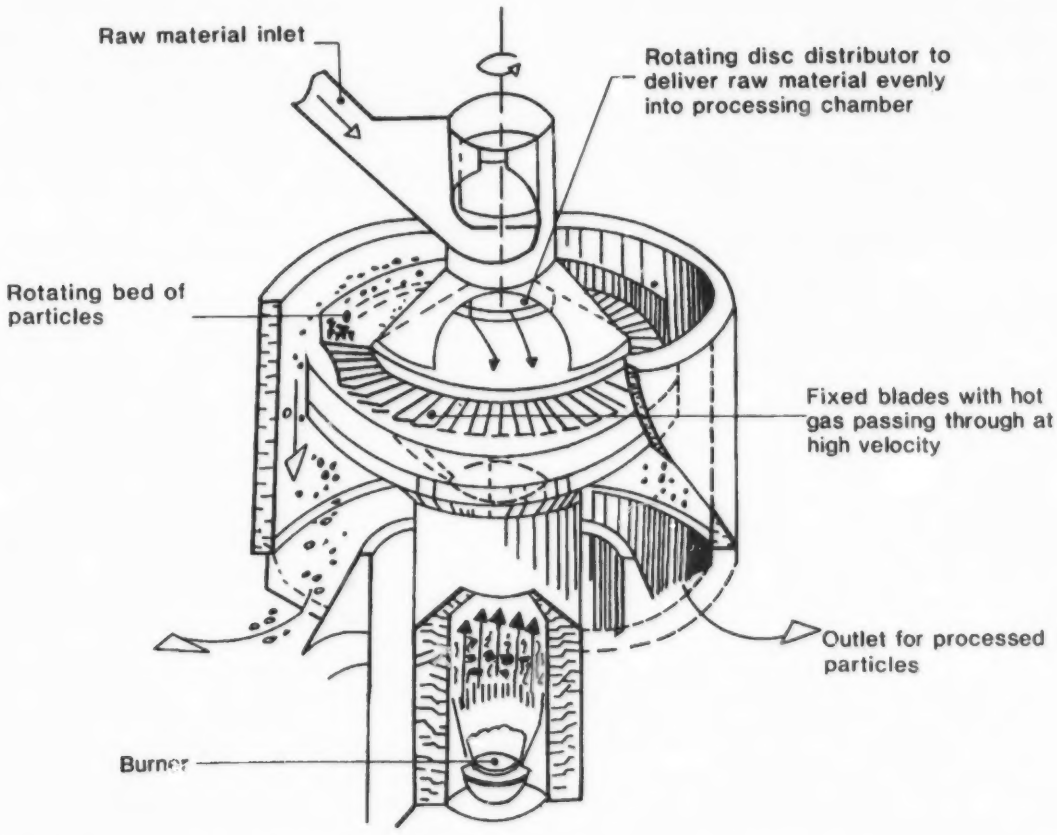
Raw material inlet
Rotating disc distributor to deliver raw material evenly into processing chamber
Rotating bed of particles
Fixed blades with hot gas passing through at high velocity
Outlet for processed particles
Burner

Figure 4. One configuration for the Torbed toroidal fluidized bed furnace *after* Dodson 1986; Torftech 1983, 1984).

Another potential application of vermiculite suspensions, currently the subject of research at ICI, is vermiculite-based foam. Foams are readily produced by introducing small air bubbles into a suspension with a maximum solids content, while still retaining flow characteristics. Just prior to formation of the foam, water is added as a stabilizing agent. Experiments determined that the addition of magnesium oxide produced foams with the highest compressive strengths due to the formation of crystal bridges between lamellae (Ballard and Rideal 1983).

Production of these vermiculite-based products is presently being undertaken on a pilot-plant level, and various industries are currently studying their use. Continuing research will probably extend the range of uses for these products.

A careful analysis of a deposit is essential if it is to be exploited to its full potential.

Geology of Vermiculite Deposits

Worldwide, virtually all vermiculite deposits are associated with igneous or metamorphic rocks of mafic to ultramafic composition, that have been invaded by silicic magmas or carbonatites.

Harben and Bates (1984) distinguished three general types of vermiculite deposit; these are:

1. formed within large ultramafic intrusive masses, such as pyroxenite plutons, cut by syenite or alkalic granite, and by carbonatitic rocks and pegmatites
2. associated with ultramafic intrusive bodies, such as dunite and unzoned pyroxenite and peridotite, cut by pegmatite and syenitic or granitic intrusives
3. formed from ultramafic metamorphic rocks such as amphibole schist in contact with pyroxenite or peridotite and cut by pegmatite

The vermiculite at Libby, Montana and Palabora, South Africa are examples of type 1 deposits, which produce approximately 93 percent of the world's vermiculite. Type 2 is typified by the Blue Ridge Mountain area of North Carolina, and type 3 by the Enoree district in South Carolina.

The largest known deposit of vermiculite occurs in the Rainy Creek Complex, near Libby, Montana, shown in Figure 5. The host rock is a zoned pyroxenite which consists of a core of biotitite, an inner ring of biotite pyroxenite and an outer ring of magnetite pyroxenite. The pyroxenite is intrusive into the Wallace Formation (principally argillites and calcareous argillites) of the Precambrian Belt Series metasediments, and is dissected by a younger mass of syenite and alkalic syenitic dykes. A small nepheline mass which cuts the pyroxenite complex, and the presence of fenitized Belt Supergroup rocks, suggest the presence of a carbonatite at depth (Bush 1976).

The Palabora deposit, the other major source of vermiculite, occurs in the Palabora carbonatite complex (*see* Figure 6). The complex contains three separate igneous cores, the northern most of which hosts the vermiculite mine. For this part of the complex, the general lithological sequence from the margin to the core is: feldspathic pyroxenite; pyroxenite; an apatite-bearing pegmatoidal-pyroxene–phlogopite-vermiculite assemblage; and finally, an olivine-serpentine–phlogopite-vermiculite pegmatoidal assemblage (Harben and Bates 1984). The mineralization, which averages 22 percent vermiculite, has a maximum depth of 40 to 50 m, below which it changes to unaltered phlogopite (Clarke 1981).

PERTH STUDY AREA

Previous Mapping

H.G. Vennor and R.W. Ellis worked in the general area of Frontenac, Leeds and Lanark counties at the turn of the century. The Precambrian geology was examined by Dugas (1950) and Wilson and Dugas (1961), and was incorporated into compilation maps by Hewitt (1964) and Kingston et al. (1985). The Paleozoic geology was mapped by Williams and Wolf (1984). Hoadley (1960) and Guillet (1962) examined the vermiculite occurrences in the Perth Area.

General Geology

The rocks in the map area can be stratigraphically subdivided into three age groups: the oldest Grenville Supergroup metasedimentary rocks are cut by Late Precambrian intrusive rocks, and both are overlain by Paleozoic sedimentary rocks.

GRENVILLE SUPERGROUP METASEDIMENTARY ROCKS

The Grenville Supergroup is represented within the study area by the sequence: marble (limestone), quartzite (sandstone), and aluminous quartzofeldspathic gneiss (shale). The metasediments have been isoclinally folded about a northeast-striking axis which is generally coincident with the Grenville structural fabric, but locally the structure is more complex. There are no conspicuous faults, and only discontinuous jointing is present within the Precambrian terrain.

The metasedimentary succession has been subdivided into: calcareous metasediments—crystalline limestone, dolostone and metamorphic pyroxenite; and clastic metasediments—quartzite and quartzofeldspathic gneiss.

Calcareous Metasediments

Crystalline limestone and dolostone represent the oldest stratigraphic units in the area and principally outcrop in a band along the north shore of Pike Lake on the Westport road. The marble is generally white to buff coloured, with a medium- to coarse-grained, granular to massive texture. Phlogopite, diopside, serpentine and disseminated graphite are common accessory minerals within the marble; the presence of allietite (Miles and Springer 1989) and corrensite (De Kimpe et al. 1987; De Kimpe and Miles 1988; Miles and De Kimpe 1988) has recently been reported. Wilson and Dugas (1961) observed "...inclusions of fragments of younger rocks, around which the limestone has molded itself as in a plastic flow" in several localities within the marble. These features were also noted at several locations during the present study.

Pyroxenite occurs in two northeast-striking bands. The southern band, in the vicinity of the Olympus pit, appears to be of metamorphic origin, produced from an "alteration of a dolomitic marble by the action of siliceous emanations from igneous intrusions" (Wilson and Dugas 1961). It is a light green, medium- to coarse-grained rock, with a competent to friable texture. Accessory minerals include various proportions of tremolite,

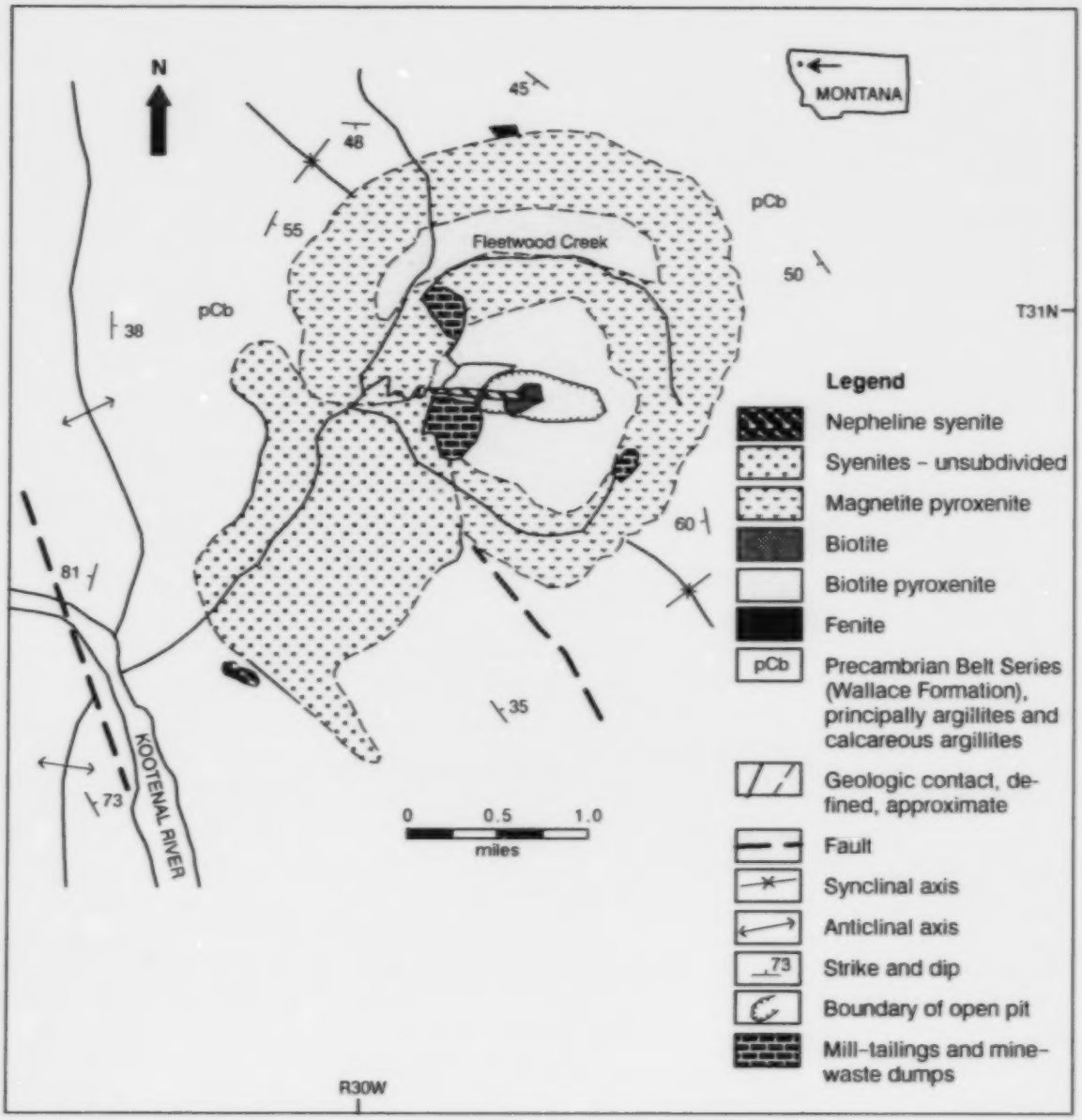

Figure 5. Simplified geological map of the Rainy Creek Complex, near Libby, Montana; *after* Bush (1976).

talc, serpentine, phlogopite, hydrobiotite, aliettite, calcite ± dolomite, quartz and vermiculite. The northern band of pyroxenite, which may be of igneous origin, is cut by phlogopite dykes. These dykes were mined in the past as sources of phlogopite, as evidenced by the numerous trenches and pits (up to 7.6 m deep) on Lots 16, 17, Concession 8, North Burgess Township; phlogopite plates up to 0.45 metres in diameter were observed in several pits. The phlogopite dykes are hosted in pyroxenite. A more detailed examination of the pyroxenite in the vicinity of the Olympus pit will be presented later in the report.

Vermiculitization of phlogopite has been observed in both pyroxenite bands, but only in the southern band does any significant quantity of vermiculite appear to have developed.

Clastic Metasediments

The quartzite unit includes a pure massive white unit, similar in appearance to vein quartz, which may contain iron oxides. A second unit, contains tremolite-actinolite and locally talc, and is interbedded with thicker bands of quartzite. A third unit contains interbedded quartz and

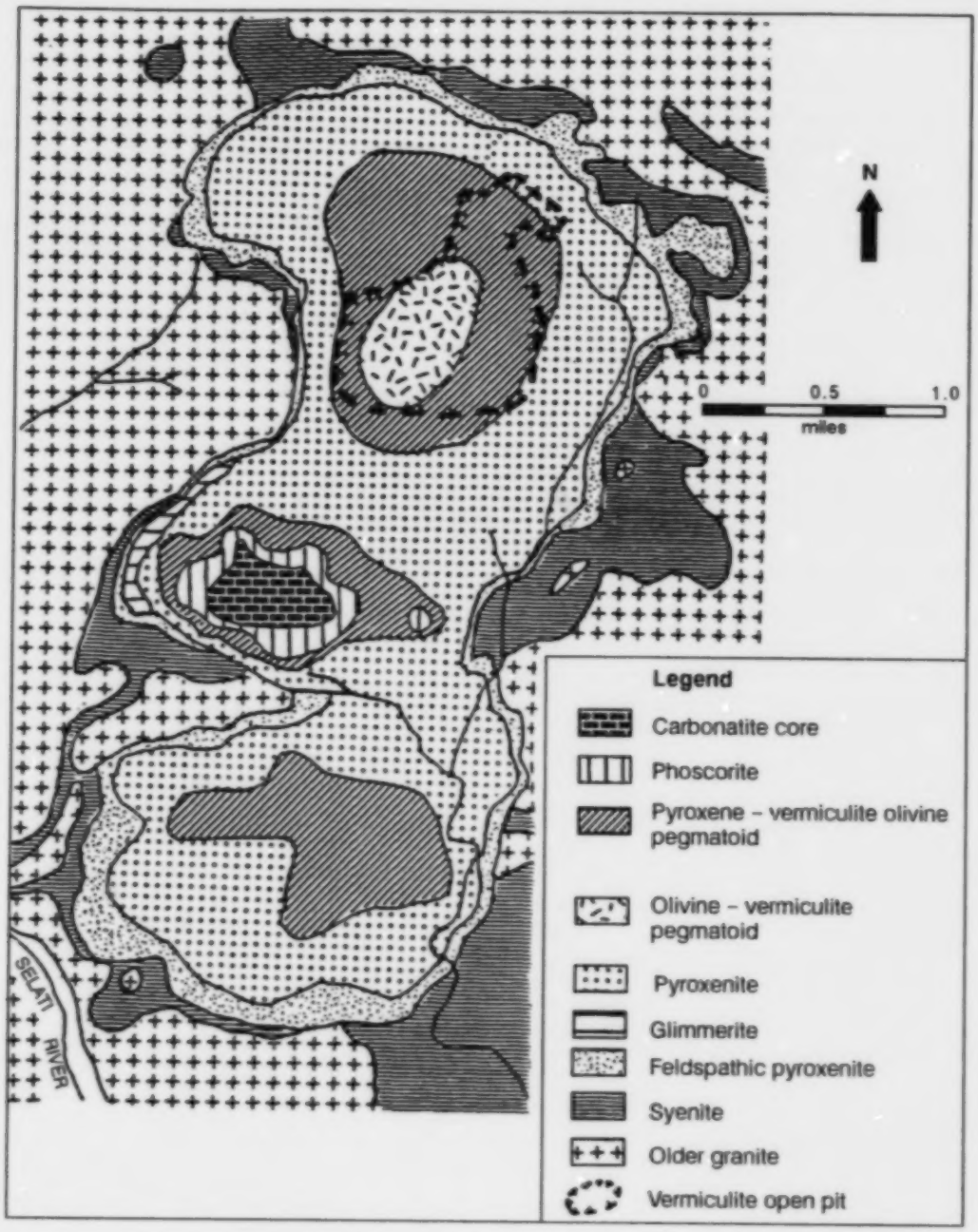

Figure 6. Simplified geological map of the Palabora Igneous Complex, South Africa, showing the approximate location of the vermiculite open pit; *after* Harben and Bates (1984).

brown crystalline marble, which locally exhibit flow deformation. Small lenses of pyroxenite occur within the quartzite; they contain minor amounts of disseminated hydrobiotite, vermiculite and phlogopite.

Quartzofeldspathic paragneiss outcrops south of Pike Lake and on a few islands close to the south shore. It is also found as migmatitized remnants of rusty or graphitic paragneiss within granitic intrusives. Garnet-biotite paragneiss is the most common rock type of this unit, but hornblende-rich paragneiss occurs in a few, small, isolated pockets within the more extensive biotite-rich rock. Common accessory minerals within the paragneiss include biotite, garnet, hornblende and graphite.

In the southern portion of the map area, the paragneiss has been intruded by syenite and diorite.

Late Precambrian Intrusive Rocks

Wilson and Dugas (1961) inferred that the intrusive masses were emplaced through "the processes of metasomatism and by doming of the adjacent sedimentary rock, particularly where the invaded rock is the most susceptible, as in the case of garnet gneiss." This has resulted in a gradual zonation from massive syenite in the centre of the plutonic body to a syenite gneiss, syenite migmatite and finally unaltered garnet gneiss. This change was also observed by William and Dugas (1961) in the Perth area and by Wynne-Edwards (1967) in the Westport area to the south. Syenite migmatite represents a transitional phase between rocks of igneous and sedimentary origin.

The syenite is variable in texture and grain size, but commonly contains microcline, plagioclase, biotite and hornblende, with the accessory minerals sphene, magnetite-ilmenite and apatite. Diorite occurs as irregular patches, associated with remnant rusty paragneiss, within the syenite migmatite in the southeastern part of the study area.

Pegmatite dikes, consisting essentially of microcline and quartz, cut the granitic rocks of the area.

Wilson and Dugas (1961) suggest that quartzite was transformed into granite, and garnet gneiss into syenite, through chemical re-adjustment during the granitizing process that formed the syenite migmatite complex.

Paleozoic Rocks

The undulating Precambrian erosional surface was unconformably overlain by a variable thickness of Cambro–Ordovician strata. Recent remapping by the Ontario Geological Survey (Carson 1982a, 1982b; Williams and Wolf 1984a, 1984b) has led to the rationalization of the terminology of this lowermost unit of the Sauk Sequence (Cambrian to early Ordovician): all of the siliciclastic sedimentary rocks which underlie the Beekmantown Group (whose base is arbitrarily defined as the first carbonate bed) are referred to collectively as the Potsdam Group. All feldspathic sandstones and conglomerates within the Potsdam Group are termed the "Covey Hill Formation", and the nearly pure quartz sandstones and conglomerates are called the Nepean Formation.

Within eastern Ontario, the "Covey Hill Formation" outcrops only in isolated, down-faulted blocks and is never observed in contact with the Nepean Formation. Its impure mineralogy and lack of rounded quartz grains and carbonate rock fragments indicate that it is older than the Nepean Formation. Nevertheless, the exact age of the "Covey Hill Formation" remains unknown; it could be anything from late Proterozoic to early Ordovician. A Lower Ordovician conodont fauna recovered in the Ottawa area (Brand and Rust 1977) gives the generally accepted best age estimate for the Nepean Formation.

The "Covey Hill Formation", with its very immature mineralogy, represents first-cycle debris derived from the Precambrian Shield; it is characteristic of the source rock from which the quartz-rich Nepean sandstones were derived by wind action.

At the basal unconformity some indication of a post-Grenvillian–pre-Potsdam erosional event, which may have influenced vermiculite formation, is locally recorded. At Sloan's quarry on the western shore of Rideau Lake, 8 km west of Stanleyville, a hematite-cemented Covey Hill conglomerate indicates terrestrial weathering in late Precambrian times (Dalrymple and Wolf 1988). Twenty kilometres to the northwest, at the Playfair (Dalhousie) iron mine, a similar post-Grenvillian conglomerate contains pyrite pervasively oxidized to hematite (Rose 1958). This oxidation can be equally attributed to pre-Potsdam surficial weathering, or to more recent deep weathering, based on existing field evidence. Regional relationships suggest that it is pre-Nepean.

Regardless of age considerations, however, there are indications of the terrestrial weathering which, in major vermiculite deposits of the world, is known to be a necessary precursor to good vermiculite development.

VERMICULITE OCCURRENCES IN THE PERTH AREA

The Perth area vermiculite occurrences are widely distributed throughout the Stanleyville–Pike Lake area. Significant occurrences are the P. Farrell property and the Olympus Mines Ltd. property. Numerous other small occurrences, which, in the form of veins and disseminations within marble, are present within the map area; they are recorded on Figure 7 (back pocket).

The only other significant occurrence of vermiculite reported in southeastern Ontario is the Goshawk Mines Ltd. property, located north of Peterborough in Cavendish Township; a brief description of this property is presented in Appendix B.

P. Farrel Property (Norden Vermiculite Ltd.)

LOCATION AND ACCESS

The property is situated on Lot 14 and the north half of Lots 15 and 16, Concession 9, North Burgess Township, Lanark County, approximately 11 km southwest of Perth on county road 10.

PREVIOUS WORK

North Bay Mica Co. Ltd. trenched and diamond drilled the property in 1951–1952. Northern Vermiculite Ltd. optioned the property in 1956 and established a pilot-scale exfoliating plant in Perth; in 1957, this was replaced by a small, commercial plant at Glen Tay. E.A. Vacheresse of Northern Vermiculite Ltd. reported that 15 000, 4-cubic-foot bags were produced from these two small exfoliating plants, before operations ceased (Guillet 1962). The bulk of the ore apparently came from a

small open pit which is presently about 12 by 45 m in area.

In 1958, Rochester and Pittsburgh Coal Company optioned the property and conducted 610 m of diamond drilling. E.A. Vacheresse drilled an additional 13 holes in 1960 and in 1961, the company was renamed Norden Vermiculite Ltd. (Guillet 1962).

GEOLOGY

The detailed geology of the property, as shown in Figure 8 (*after* Guillet 1962), could not be observed in the field due to caving or infilling of trenches, flooding of the pit (45 by 12 m), and recent road construction which obliterated a considerable number of the trenches in the area.

Guillet (1962, p.11) describes the main zone as "a steeply plunging pod of coarse grained phlogopite-diopside gneiss enclosed by a moderately silicated marble. The zone, measuring some 200 feet by 70 feet, elongated in a northeast-southwest direction, and plunges to the east at 75°." The degree of vermiculitization is generally low.

Small lenses of biotite schist containing a high degree of vermiculitization occur elsewhere on the property. Partially hydrated, light coloured mica occurs as disseminations within the marble band. Several small (up to 1.5 m) syenitic dykes were reported by Guillet (1962) to transect both the vermiculitized zone and wall rocks, generally striking north-east and dipping easterly.

Deep weathering, a feature associated with vermiculite at the Olympus Mines Ltd. property, is not an apparent feature of this occurrence.

Olympus Mines Ltd. Property

LOCATION AND ACCESS

The property is located on the north half of Lots 17 and 18, Concession 8, North Burgess Township, (100 acres are patented in Lot 17), approximately 800 m southwest of Stanleyville and approximately 13 km by road from Perth.

HISTORY OF THE PROPERTY

In 1950, G.C. Bruce of the Industrial Minerals Branch, Ottawa discovered the deposit. Siscoe Vermiculite Mines Limited, a new subsidiary of Siscoe Gold Mines Limited, optioned the property a few days later and engaged in a program of auger drilling and trenching. In 1959, the property was sold to Olympus Mines Ltd. which began developing the property by drilling 45 auger holes and 2 diamond-drill holes, and, in June 1960, by developing the open pit. By 1963, the stockpile was an estimated 126 000 m^3 (165 000 cubic yards) of vermiculite-bearing material, produced from a 305 m (1000 ft.) X 91 m (300 ft.) X 9 m (30 ft.) pit (Guillet 1962, p.8). A processing plant was constructed by 1965 and some material was processed, but the operation proved uneconomic.

In 1968, a consortium based in Ottawa, Worldwide Energy Company Limited, optioned the ground; it retained G.H.D. Consultants of Toronto to evaluate the property in 1969. G.H.D. Consultants drilled four holes, totalling 575 m and trenched approximately 610 m (*see* Appendix C). Bulk samples of 450 kg and 4500 kg were taken from the east face of the pit. The 450 kg sample was sent to Montreal for analysis and the 4500 kg sample was retained for a batch test in the existing plant. The results of these tests are not available. Analysis of drill results concluded that this deposit could support a 270 t/day operation for 10 years, with the mill head grading 20 percent vermiculite (Cunningham 1969; Guillet 1962). The property is currently owned by Canalex Resources Ltd.

GEOLOGY

The geology in the immediate vicinity of the property (Figure 9) consists of Grenville Series rocks: paragneiss, quartzite, calcitic and dolomitic marble and metamorphic pyroxenite. The vermiculite occurs in thinly banded, pale blue-green, serpentinized metamorphic pyroxenite which is flanked on both sides by hornblende to biotite paragneiss that changes to quartzite northwest of the pits and disappears into swampy ground to the southeast.

The main mineralized zone strikes 052°, dips 80° northwest and can be observed along the northeastern face of the pit. Diamond drilling by G.H.D. Consultants, in 1969, established an average width for the zone of 40 m, ranging between 24 m and 45 m, with a minimum length of 425 m. Trenching showed that, in the centre of pit, the vermiculitized zone is only 24 m wide (Cunningham 1969; *see* Appendix B). Guillet (1962) reported that three additional vermiculite-bearing zones of limited extent occur on the property.

The mineralized zones consist of thin bands, each less than 2.5 cm wide, of pale brown hydrobiotite-vermiculite–rich rock alternating with almost barren, altered, light green, diopsidic rock. The hydrobiotite-vermiculite flakes are usually less than 3 mm in diameter, and range in colour from pale brown through amber and olive-grey to silvery. In addition to the banded and disseminated mineralization found within the main zone, there are vertical veins of coarser grained phlogopite-hydrobiotite up to 8 cm across. This feature is evident on both the northeastern and northwestern faces of the pit, but is more prevalent on the northwestern face.

The rock of the hanging wall consists of relatively hard, competent, cream-grey, less intensely altered pyroxenite. The contact between the wall rock and the main zone is irregular due to interbanding of the vermiculitized pyroxenite with barren pyroxenite. This is evident on the surface and in samples obtained from the current drill program. Where it is exposed north of the orebody, and further from the presumed source of the hydrothermal solutions, the dominantly diopsidic pyroxenite becomes enriched in tremolite which occurs as brown, prismatic, vitreous grains. Here, the pyroxenite

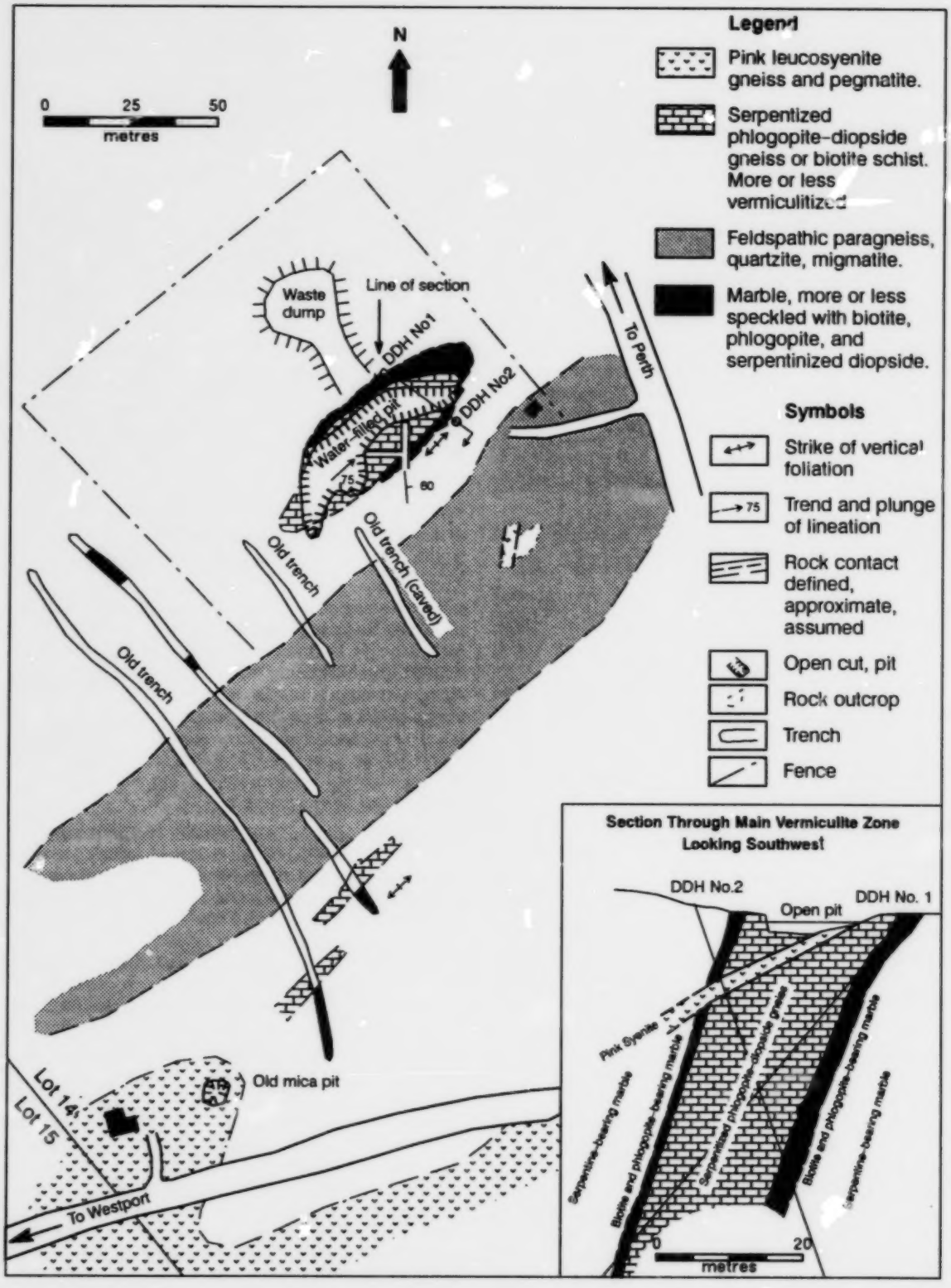

Figure 8. Geological map of the P. Farrel (Norden) property *(after* Guillet 1962).

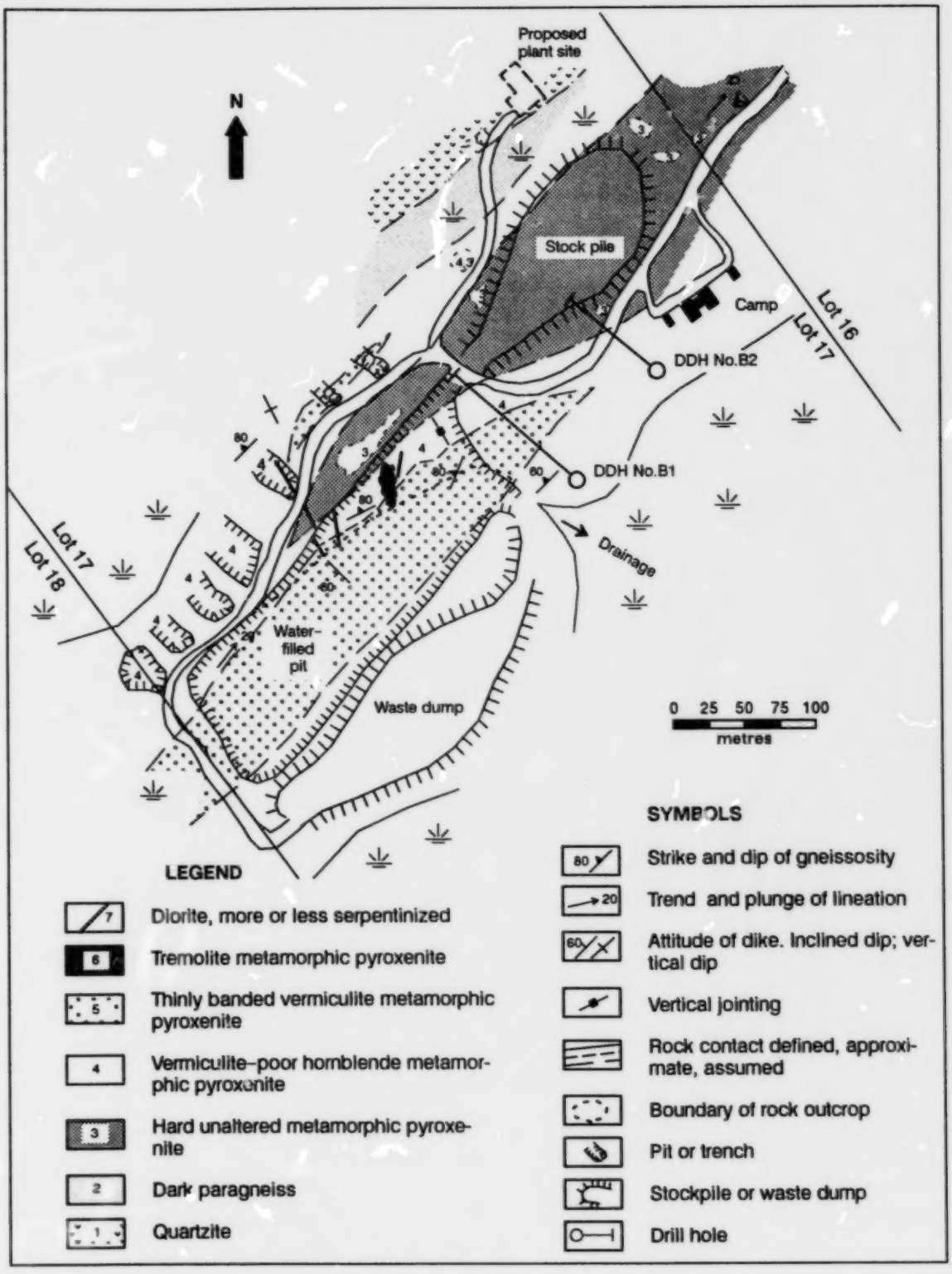

Figure 9. Geological map of the Olympus Mines Ltd. property (*after* Guillet 1962).

is interbanded conformably with quartzite and actinolite-tremolite-talc schist.

The main zone is dissected by undulating, horizontal and occasionally vertical, fractures and intruded by dioritic dikes (Photo 1). The fractures are generally less than 10 cm thick and are filled with grey-blue, massive to fibrous talc.

Near the present surface, the host pyroxenite is highly friable, resembling sand in texture and appearance (*see* Photo 1). This grey saprolitic zone is composed of various proportions of hydrobiotite, vermiculite, allietite, corrensite, tremolite, talc, serpentine and phlogopite, with minor diopside, chlorite, iron oxides, dolomite, calcite, and pyrite (N. Miles, Agriculture Canada, Ottawa, personal communication, 1989).

The diopside, which is greenish white, is medium grained, hypidioblastic to xenoblastic in habit, and has a woody appearance. However, little of the diopside remains due to the extreme nature of the alteration. Thin section examination indicates an intergrowth with amber coloured, idioblastic to hypidioblastic tremolite. A brown alteration observed along fractures and cleavages within the diopside has been identified by electron microprobe analysis as talc stained with iron oxides (Wolfson 1980). This feature is evident in Photo 2.

Near the surface there are several indications of a later episode of alteration. For example, the top 9 to 12 m is looser and more weathered than the rocks below. This can be observed in (1) the drillcore; (2) the pit face where diorite dikes (*see* Photo 2, Photo 3) in the main zone have been partly serpentinized, steatized and chloritized, weathering to an orangish colour which stains the pit face; (3) thin sections, where alteration products, e.g., talc, are observed to be dusted or stained with iron oxides; and (4) the presense of the grey saprolitic zone containing grey-green, clay-sized allietite coating coarser, crumbly, phlogopite-talc grains (Miles and Springer 1989). This alteration decreases from the present surface downwards and, from its distribution, appears to be the result of weathering.

Wilson and Dugas (1961), and Rose (1958), present incidental evidence of erosion and weathering before the Paleozoic. It is possible that today's surface is, in part, the re-excavated Precambrian unconformity underlain by material generated during pre-Paleozoic weathering. This may be important in understanding the distribution of the vermiculite because a paleoweathering surface would closely define the stratigraphic position of the vermiculite. Examples from other vermiculite deposits such as those at Libby, Montana (Boettcher 1966), and South Carolina (Libby 1975) suggest that high-grade metamorphism produces biotite or phlogopite from which vermiculite is subsequently formed by meteoric waters under weathering conditions.

SEPARATION AND BENEFICIATION STUDIES

Previous Testing

Wilson (1957) performed tests on vermiculite samples submitted by Northern Vermiculite Limited (P. Farrell property), to obtain data on differential reduction using

Photo 1. Altered dioritic dyke (far right) intruding highly friable saprolitic pyroxenite; northwest face, Olympus Mines Limited open pit.

Photo 2. Intergrown diopside and tremolite, with talc alteration; by its distribution, the talc appears to be the result of weathering: Tr–tremolite, D–diopside, T–talc alteration with iron oxide stain.

three different types of crushers. A usable 28-mesh product could not be produced, but partial concentration was obtained by electrostatic separation and by air tabling.

However, the majority of testing was performed on samples obtained from the Olympus Mines Limited property (Wilson 1961, 1969; Wyman 1964). Wilson (1961) tested 30 samples of split diamond-drill core, 2 samples from the surface of the pit, 1 from the stockpile and an auger sample from the floor of the pit. These samples were evaluated for weight percentage vermiculite, weight percentage insulation grade vermiculite, bulk density of exfoliated product and effect of firing temperature on exfoliation. Results indicated an average of 25 percent vermiculite (7.2 to 41.7 percent) from samples taken from the pit floor, of which over 65 percent was in the minus 14- to plus 48-mesh size range. An average of approximately 15 percent of the product met ASTM size specifications for insulation, while the bulk was suitable for plaster aggregate. The exfoliated products taken from below the level of the pit, however, had unit weights much in excess of ASTM specifications for use as aggregate in gypsum plaster. Exfoliated products obtained from the stockpile were within ASTM specifications, close to its upper limit. Varying the firing temperature between 1700°C and 2000°C on arbitrarily selected samples of minus 28- to plus 48-mesh material had no appreciable effect on the degree of exfoliation.

Wilson (1961) experimented with several beneficiation methods and concluded that neither electrostatic nor magnetic separation were effective in concentrating the vermiculite. Only partial concentration was obtained with heavy liquid separation, using liquid of specific gravity 2.8).

Wyman (1964) conducted further testing on two 1800 kg samples to determine a suitable beneficiation method. Separation and beneficiation techniques employed included self-grinding, wet tabling, Wilfley tabling, jigging, and a Humphreys Spiral, in conjunction with a diagonal deck shaking table, and dry testing using an air table and differential rollers crushing. He concluded that wet tabling methods were unlikely to succeed since even short exposure to water was sufficient to induce breakdown of the vermiculite. Wet jigging a plus 8-mesh feed produced only a small quantity of high-grade vermiculite. Using differential rollers on dry feed and concentrating by air tabling, a product containing 75 percent vermiculite with a 66 percent recovery could be obtained and this could be upgraded to 86 percent vermiculite with a 30 percent recovery (Wyman 1964).

Wilson (1969) analyzed three samples of split core submitted by G.H.D. Consultants Limited for vermiculite content, vermiculite flake size and bulk density of the exfoliated vermiculite recovered. The samples contained 15 to 19 percent recoverable vermiculite; with 68 to 77 percent of the vermiculite in the minus 8- to plus 48-mesh size. Although the minus 8- to plus 48-mesh fraction did not meet ASTM bulk density specifications for concrete aggregates, Wilson (1969) suggested that a reduction in bulk density might be achieved through more rapid heating during the exfoliation process.

CURRENT TEST WORK

Sample Techniques

A 160 kg chip sample and a 35 kg drill core sample were taken from the Olympus Mines Limited property, during the present investigation, in order to conduct preliminary beneficiation testing.

The chip sample, taken across a 15 m section of the cleaned northeastern face of the pit, was rich in hydrobiotite-vermiculite.

Core samples of a deeper section of the mineralized zone were obtained from an inclined drill hole striking 140° and dipping 57°, (hole ST-1, Appendix C) that is parallel to the northeastern pit face. The hole was drilled to a vertical depth of 43.6 m and is 52.1 m in length. Recovery of the first 12.2 m of core was in the form of sludge, due to the highly weathered nature of the rock. Various techniques, such as a rotating core barrel, varying the drill speed and water flow, and changing the core size, were employed in an unsucessful attempt to increase core recovery. The core was split; half was shipped to the Ministry of Northern Development and Mines core storage facility in Tweed, and half was sent to CANMET for testing purposes.

Separation and Beneficiation

SAMPLE PREPARATION

The chip sample was screened into four size fractions: (1) less than 2.0 to greater than 0.6 mm, (2) less than 0.6 to greater than 0.3 mm, (3) less than 0.3 to greater than 0.15 mm, and (4) less than 0.15 mm. Material larger than 2.0 mm was crushed by a dual roll crusher and rescreened, while the fraction less than 0.15 mm was discarded. The drill core was divided into two parts: sample 1 was the upper part of the hole, from 12.3 to 27.7 m; sample 2 was most of remainder, from 27.7 to 43.1 m. Each sample was crushed independently using a dual roll crusher in four consecutive stages with intermediate sizing at 2 mm, and similarly screened. Crushing became more difficult with increasing depth, resulting in more fines being generated.

DRY BENEFICIATION

Magnetic Separation

The individual size fractions of each of the three samples were processed in a Carpco magnetic separator at different field intensities. No mineral concentrations were apparent at either low or high coil current.

Electrostatic Separation

Results from electrostatic separation trials were unsatisfactory. At low voltage (5000 V) "skin" vermiculite (individual delaminated flakes) was concentrated but the vermiculite books remained in the reject portion, and at higher voltages (> 10 000 V) recovery increased but remained unacceptable.

Air Tabling

Gravimetric separation was not successful because of the small difference in specific gravity between the minerals in the ore, and because the vermiculite books have an aspect ratio similar to that of associated tremolite and other gangue minerals.

A disc pulverizer was used in an attempt to enhance the shape difference between the vermiculite and other gangue constituents. Regardless of the gap distance, delamination occurred, resulting in the production of too much "skin" vermiculite.

WET BENEFICIATION

Flotation

The 0.15 to 0.3 mm size fraction of the various samples were tested for flotation characteristics using a laboratory-type Denver flotation cell, to examine the possibility of upgrading the vermiculite content without further optimization (Table 12). It is notable that for the weathered sample, the best results were obtained using an alkaline pulp with tertiary amine as the vermiulite collector, while vermiculite from drill core samples floated only under acidic conditions.

Vermiculite in the 0.6 to 2.0 mm size fraction was difficult to float in a conventional flotation cell. Attrition of the cell propeller resulted in delamination of the coarse vermiculite and excessive production of slimes. Lamothe and Wang (1986) suggested that these problems may be minimized by using a column flotation cell instead of a mechanical type.

Hydrogen Peroxide Tests

Aliquots of the 0.15 to 0.6 size fraction of the chip sample were treated in various concentrations of an

Table 12. Flotation test results.

Sample description	pH[1]	Reagent	Comments
–0.3, +0.15 mm (chip sample)	10	tertiary amine[2]	vermiculite floats with some talc and tremolite; 60% vermiculite in float product
–0.3, +0.15 mm (chip sample)	4		poor flotation of vermiculite
–0.3, +0.15 mm (chip sample)	4	oleic acid[3] & frother	flotation of talc with some vermiculite
–0.3, +0.15 mm (core sample)	10	amine[2]	no flotation
	4	amine[2]	vermiculite floats with impurities; float product contains 70% vermiculite

[1] *pH regulated with H_2SO_4 and Na(OH)*
[2] *Ethomeen T/15*
[3] *Dow D250*

aqueous solution of of hydrogen peroxide (H_2O_2). In this process, bubbles selectively form on the surface of the vermiculite until the vermiculite rises to the surface of the cell and can be removed. The most promising results were obtained during a quiet flotation using a 10 percent solution (by volume) of H_2O_2, and tertiary amine as a collector.

In one test, Lamothe and Wang (1986) skimmed off the floated material after 20 minutes; the float consisted of 95 to 98 percent exfoliated vermiculite with little "skin" vermiculite. In a second test, the floated material was skimmed off every 2 minutes; here the float consisted of 60 percent or more unexfoliated vermiculite.

PRE-EXFOLIATION METHOD

Aliquots of the chip sample, drill core sample 1 and drill core sample 2 were separately crushed and screened into four fractions: less than 2.0 to greater than 0.6 mm, less than 0.6 to greater than 0.3 mm, less than 0.3 to greater than 0.15 mm and less than 0.15 mm. The latter was discarded and the material greater than 2.0 mm was recirculated.

Each fraction was then thermally treated in a laboratory tube furnace at 2000°F to exfoliate the vermiculite. Residence time was increased with the fineness of the feed. Heat treatment was not optimized; emphasis was on upgrading and recovery of vermiculite by mechanical means (Lamothe and Wang 1986). The exfoliated fraction was separated using a Denver air table with a 300 by 500 mm deck.

For the purposes of this study, a concentrate contains more than 90 percent vermiculite by volume, a middling contains 40 to 90 percent, and a reject; less than 40 percent vermiculite. Under production conditions, the middlings would be returned to the feed point for recycling.

Preliminary testing indicated that the concentrate recovery from the chip sample was 31.1 percent by weight (61.6 percent of total volume, exfoliated), the middling was 11.3 percent by weight (9.8 percent of total volume, exfoliated) and the reject was 57.6 percent by weight (28.6 percent of total volume, exfoliated). Eighty-two percent (by volume) of the vermiculite in the mill feed reported in the concentrate; recovery increased to 93.4 percent when the middlings were recirculated.

Drill core sample 1 yielded a concentrate of 21.9 percent total weight (51.7 percent of total volume, exfoliated), representing a 72.9 percent, by volume, recovery of all vermiculite contained in the feed. For drill core sample 2, the equivalent numbers are a concentrate of 20.6 percent total weight (46.9 percent of total volume) with a recovery of 81.5 percent by volume. If the middling were to be recirculated and recovered, recovery should increase to 92.5 percent by volume (Lamothe and Wang 1986).

Tests for Asbestiform Minerals

Of considerable importance to environmentalists and government agencies is the presence of asbestiform fibres in dust from vermiculite operations. E.J. Chatfield of Chatfield Technical Company tested vermiculite, from the Olympus Mines Limited property, at the Ontario Research Foundation, Mississauga (Chatfield 1985).

Chatfield (1985) found that the vermiculite shows gradational changes of composition from the centre to the flake margins. Near the centre of each flake compositions approximate biotite and phlogopite. Towards the

Photo 3. Scroll-like tubes formed in vermiculite ore as a result of curling of the edges of variably altered phlogopite sheets; it is not certain that the alteration is solely responsible for the curling.

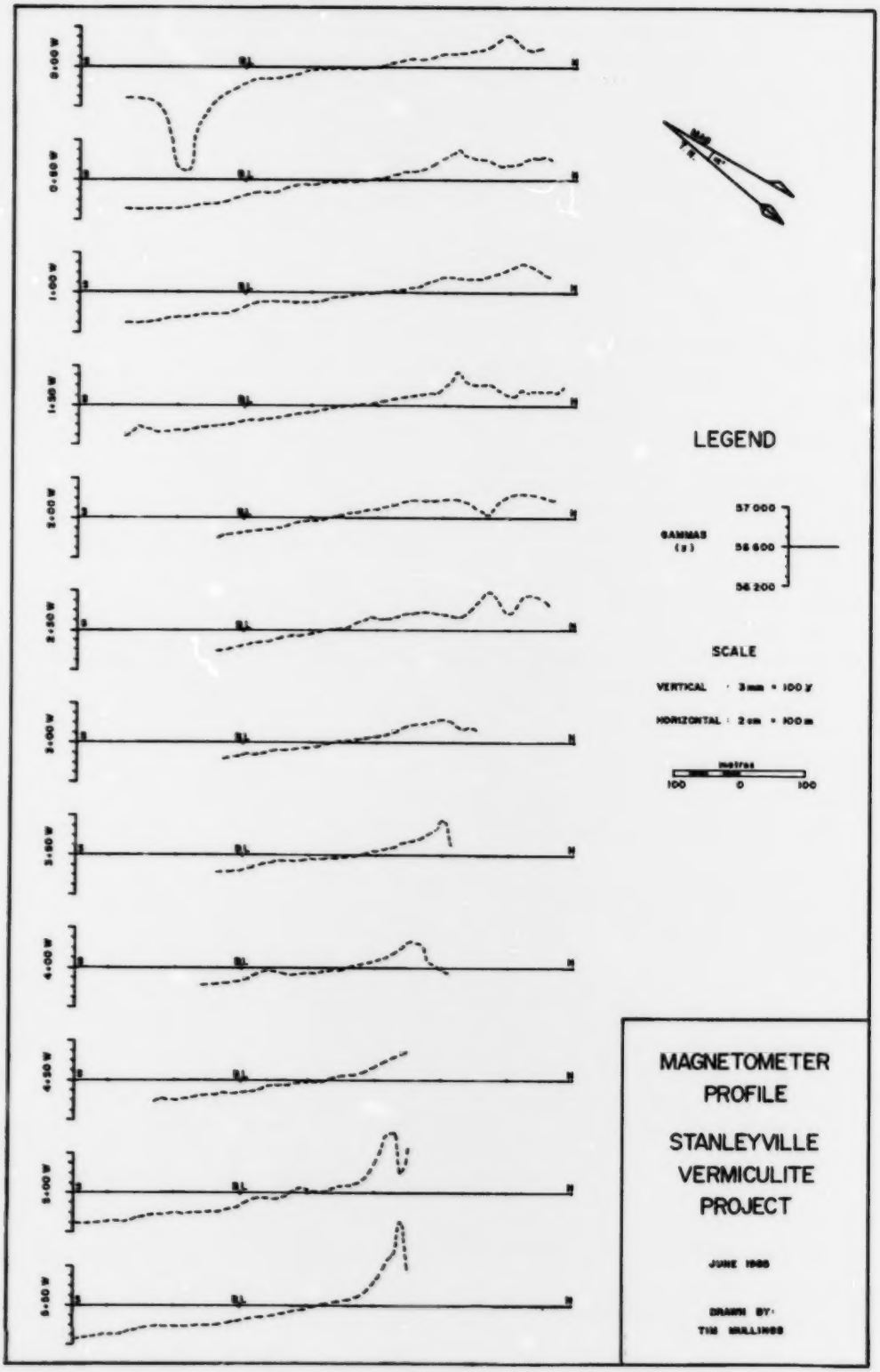

Figure 10. Line profiles from a ground magnetic survey conducted over the Olympus Mines Limited property, conducted as part of the present study.

edges of the flakes there is a progressive loss of potassium and aluminum so that the composition of crysotile is approached; simultaneously the flake edges curl into scroll-like tubes. This phenomenon is illustrated in Photo 3.

The ore contains a minute fraction of these scrolls (12.1×10^8 fibres per gram of ore, equivalent to a mass concentration of 0.11 ppm) classfied as chrysotile. X-ray diffraction confirmed the presence of a small quantity of chrysotile (N. Miles, personal communication, 1989). The scrolls average 0.5 to 0.73 μm in length, well below the 5.0 μm size that is of concern as dust hazard. There is also a very low concentration of amphibole fibres, 1.32×10^8 fibres per gram, equivalent to a mass concentration of 150 ppm.

Overall, the low concentrations present and the shaft length of the fibres produced means that the dust from this deposit is unlikely to present any health concerns.

GEOPHYSICAL SURVEY

A ground magnetometer survey was completed during the summer of 1985 on part of the Olympus Mines Limited property, by staff of the Southeastern Resident Geologist's office, Tweed.

The main objective of the survey was to determine the possibility of tracing vermiculite pods and lenses associated with stringers and dykelets of diorite, using geophysical techniques. A secondary objective was to locate buried contacts between different rock types more closely than might be done by extrapolation from outcrop areas.

The survey was conducted using a Geometrics "826" proton precession magnetometer (accurate to ± 1 gamma). Approximately 6.1 km of line were tranversed; line spacing was 50 m, with stations at 10 m intervals. The data obtained were smoothed using a five point weighted running average to eliminate erratic readings. The results were plotted on a series of line profiles and a contour map (Figure 10, Figure 11).

The survey was inconclusive. A large swamp east of the Olympus pit hides the expected source of the dykelets and stringers. Insufficient contrast between the magnetic susceptibilities of the different rock types north of the pit resulted in minimal success in delineating buried contacts. The contour map partially illustrates the contact between the quartzite interbedded with crystalline limestone and the feldspathic paragneisses in the northeast corner of the study area. The high readings in the northwest corner of the map area are due to electrical power transmission lines, and the low in the southeast corner due to a metal mill building.

A gradual increase in magnetic field strength to the north is apparent in Figure 10 and Figure 11. This probably results from a very low magnetic susceptibility in the rocks in the area of the pit, rather than a high susceptibility in the quartzites to the north. The two small positive anomalies in the centre of Figure 11 have not been explained.

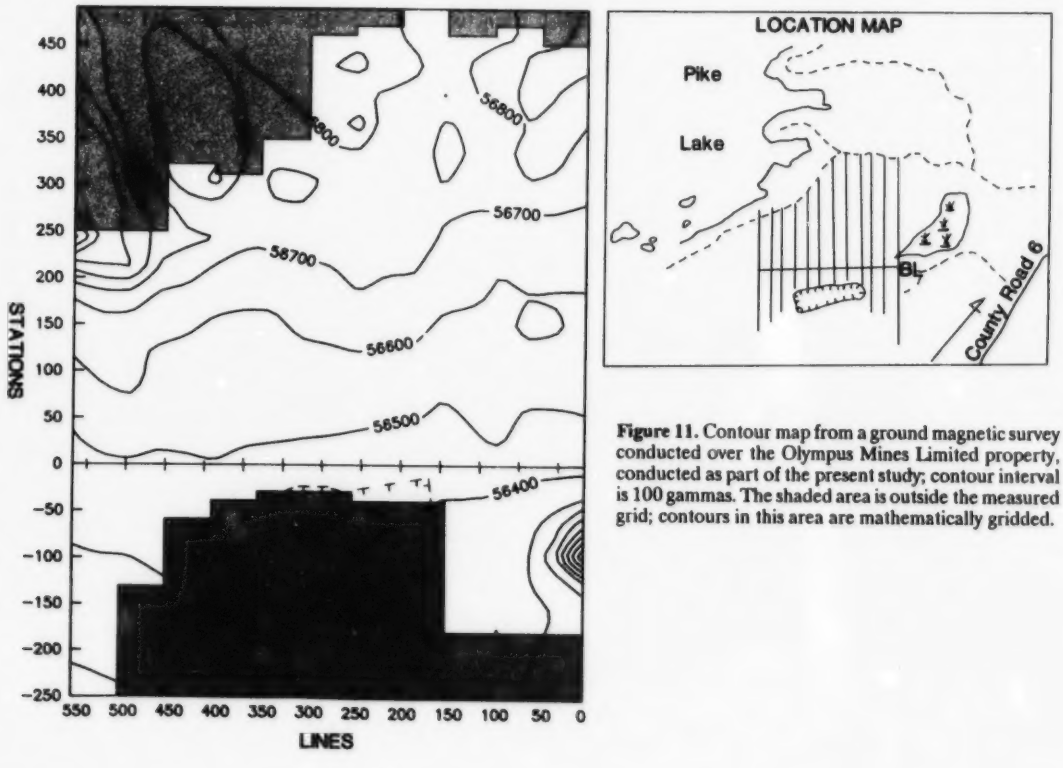

Figure 11. Contour map from a ground magnetic survey conducted over the Olympus Mines Limited property, conducted as part of the present study; contour interval is 100 gammas. The shaded area is outside the measured grid; contours in this area are mathematically gridded.

Conclusions

Shallow development of vermiculite occurs at several localities near Perth.

An extensive zone of hydrobiotite-vermiculite mineralization occurs within a highly altered pyroxenite on the Olympus Mines Limited property. Previous drilling established an average width of 40 m, and length of 425 m, for the mineralized zone. In the present study, mineralization was confirmed to a depth of 44 m.

The pyroxenite on the Olympus Mines Limited property is hydrothermal in origin, probably formed by silicification of the original dolomitic marble. The mineralization on the Olympus property consists predominantly of hydrobiotite rather than vermiculite. The presence of allietite and corrensite indicates a high degree of alteration. This alteration may be due to hydrothermal or meteoric processes, or a combination of both; however, the origin remains uncertain.

Subsequent supergene alteration (weathering), both pre-Paleozoic and post-glacial, may also have altered the upper parts of the orebody.

The ground magnetometer survey was not useful in delineating the vermiculitized zones associated with syenitic and dioritic intrusions.

The processing behaviour of the ore varies with depth. Beneficiation tests show that crushing and screening gives good separation of raw hydrobiotite-vermiculite, particularly with near surface ore. Flotation with hydrogen peroxide, using tertiary amine as the collector and under quiet conditions, is also a successful separation technique for the raw hydrobiotite-vermiculite.

A concentrate was obtained using the pre-exfoliation method with greater than 90 percent recovery. However, this method does not appear to be a viable alternative since energy requirements would be substantially higher than in operations currently in production—typically 1.5 million BTU per ton of concentrate—due to the added expense of heating waste material. However, the expense may be minimized if heat recovery methods are employed.

Small amounts of fibrous minerals are contained in the ore. Due to the low concentration of fibres, and their short length, this does not appear to constitute a health concern.

A Canadian market exists for Ontario (Perth) vermiculite of approximately 24 500 to 29 000 t/year of concentrates, plus 7300 t/year of expanded vermiculite, because the favourable location. However, problems with the contamination of asbestiform minerals within currently producing deposits could significantly increase market opportunities.

An increase in the demand for crude vermiculite of 2 percent per year is expected until 1990, in the USA. Growth in Canadian demand may be slightly lower.

An important consideration to the continued development of vermiculite resources involves the continued research and development of new technology such as improved beneficiation methods and new applications.

APPENDIXES

Appendix A

A suitable and economic exfoliation process for the type and grade of vermiculite being treated is extremely important. Figure A-1 illustrates the flow plan for a typical exfoliation plant for vermiculite.

Raw material is received into the plant, cleaned of shipping and cartage debris and stored in the buffer-stock silo. The rate of grading is geared as closely as possible to production requirements, to avoid unnecessary handling (Hitchins 1970). The sized fractions are individually exfoliated using one of a rotary, cascade, vibrating tray or injection tray type furnace, typically at a rate of 1 ton per hour.

Figure A-2 is a schematic vertical section of a typical furnace currently being employed. Upon entering the furance, the ore is spread by the baffles, then heated to between 850°C and 1100°C, at which temperature it exfoliates; typical retention time is 5 to 10 seconds (Wilson 1981).

The vermiculite is removed from the furnace by a suction fan, into a classifer system which collects the product and removes excess fines. The sized, exfoliated vermiculite is usually packaged into 4-cubic-foot bags; each bag weighs between 7 and 14 kg depending on the grade, finer grades being heavier.

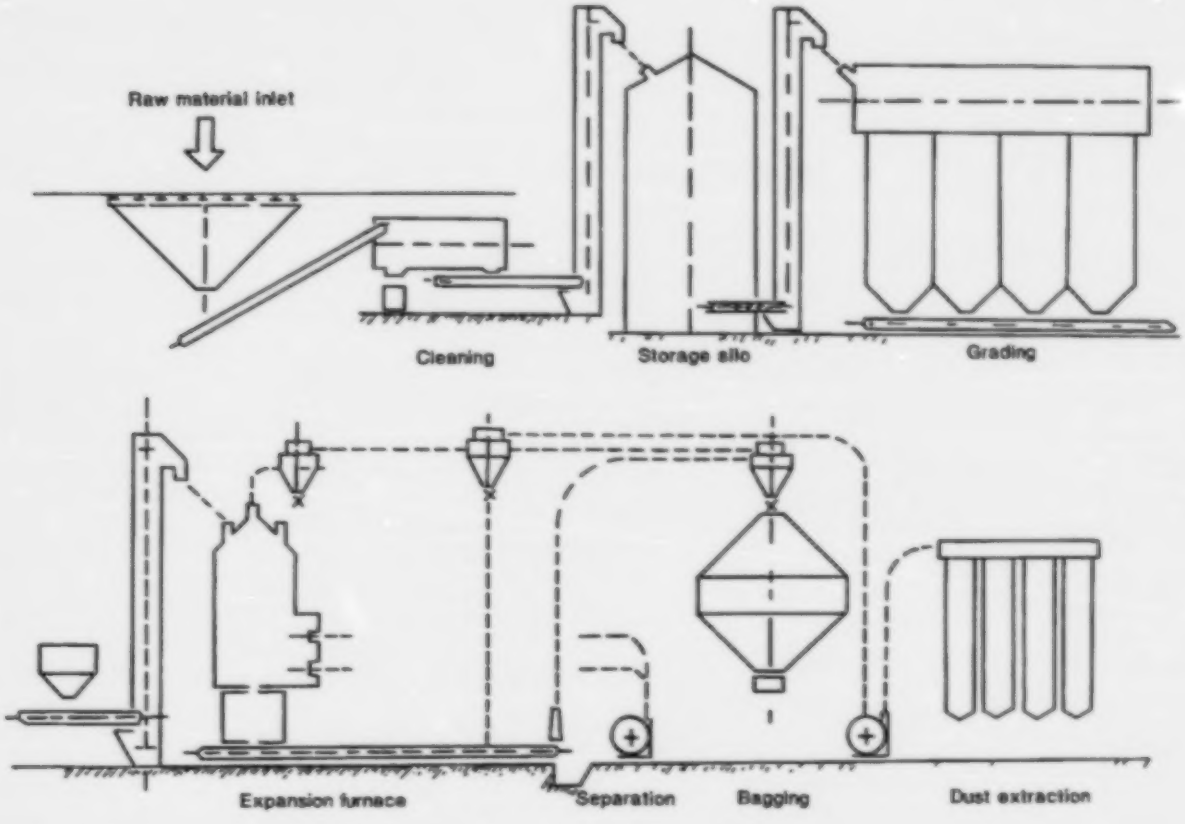

Figure A-1. Flow chart for a typical exfoliation plant for vermiculite (*after* Hitchins 1970).

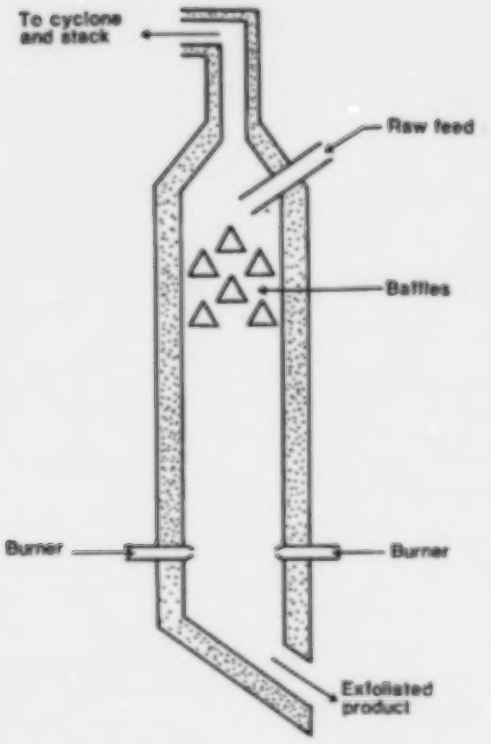

Figure A-2. Schematic section of a vertical-type furnace for the exfoliation of vermiculite (*after* Wilson 1981).

Appendix B

GOSHAWK MINES LIMITED VERMICULITE PROPERTY

Location and Access

The property is located approximately 56 km north of Peterborough, on parts of Lots 19-23, Concessions III and IV, Cavendish Township, Peterborough County. The area is covered by National Topographic System map NTS 31 D/9.

Highway 507 runs within 3.2 km of the property and cottage roads from this highway bisect the claim group. The claim group consists of 11 wholly owned contiguous unpatented claims bounded on the north by Catchacoma Lake, the east by Catchacoma Narrows and the south by Mississauga Lake (Archibald 1976, 1977a, 1977b).

History

Vermiculite was first discovered, and the ground subsequently staked, in 1950 by H.G. Greene. Periodically, the property was test-pitted and stripped in a haphazard manner, mainly in the east end of the claim group.

Globex Minerals Incorporated leased the ground in 1973 and during 1974 conducted limited auger and diamond drilling.

In 1975, Goshawk Mines Limited purchased a 100 percent interest in the claims. During 1975–1977, the company conducted an exploration program which included trenching, power auger drilling, diamond drilling and soil sampling.

Geology

The geology of the property is shown in Figure B-2 and described by Archibald (1977b) as follows:

> The claim group is underlain mainly by Grenville limestone which has been altered to a marble. Areas can be seen in this marble with disseminated flakes of amber coloured mica which has been altered to pseudo-vermiculite and vermiculite. In some areas, the mica is heavily concentrated in thick, flat dipping bands of schist, locally striking east-west.
>
> To the south, the claim group overlies the Anstruther granite batholith in the form of granite gneiss. Bordering this mass is a band of dark paragneiss, which has been altered to biotite schist and amphibolite. Narrow lenses of thin amphibolite are also found within the marble.
>
> The limestone occurs as a series of east-west trending ridges with steep north faces and gentle south dipping slopes. This bedding varies from flat lying to thirty degrees, dipping generally to the south.
>
> In areas of vermiculite-rich limestone, the tops of the ridges appear to have weathered in place to an average depth of ten feet, leaving many of the lower depression areas in a relatively unweathered state due to the protection afforded by the high ground water table. These depressions are often filled with concentrations of loose, raw vermiculite that has migrated off the nearby hillside.

Flakes are up to 1/2 inch in diameter but generally less than 1/8 inch; and vary from amber, green, and black, to silver in colour. Augering and diamond drilling has indicated that the largest concentration of vermiculite lies in the free state near surface; three zones were roughly defined (Zone A, Zone B, Zone C). Zone A covers an area 457 m (1500 ft.) long by 122 m (400 ft.) wide on the east side of the property. Exploration primarily concentrated on this '54 500 tons or 93 309 cu. yds.) zone. Archibald (1977a) estimated that a minimum of 49 400 tonnes of vermiculite, averaging 11.9 percent exfoliated vermiculite was contained within the topsoil. Zone B con-

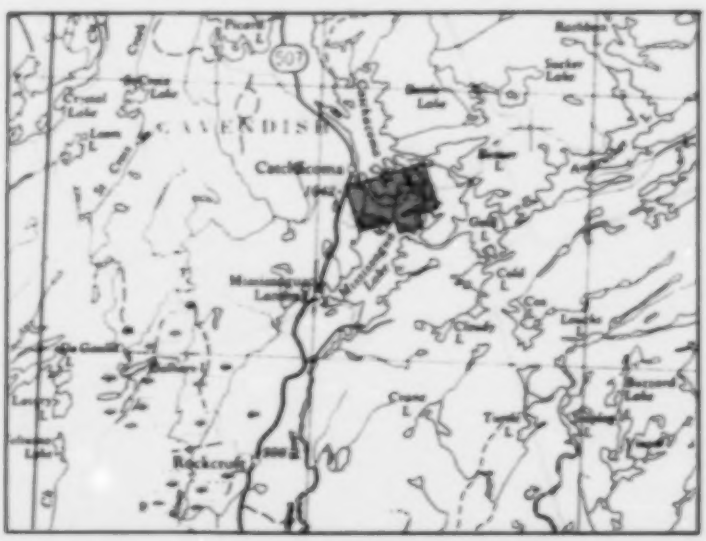

Figure B-1. Location map, Goshawk Mines Limited vermiculite property, Cavendish Township.

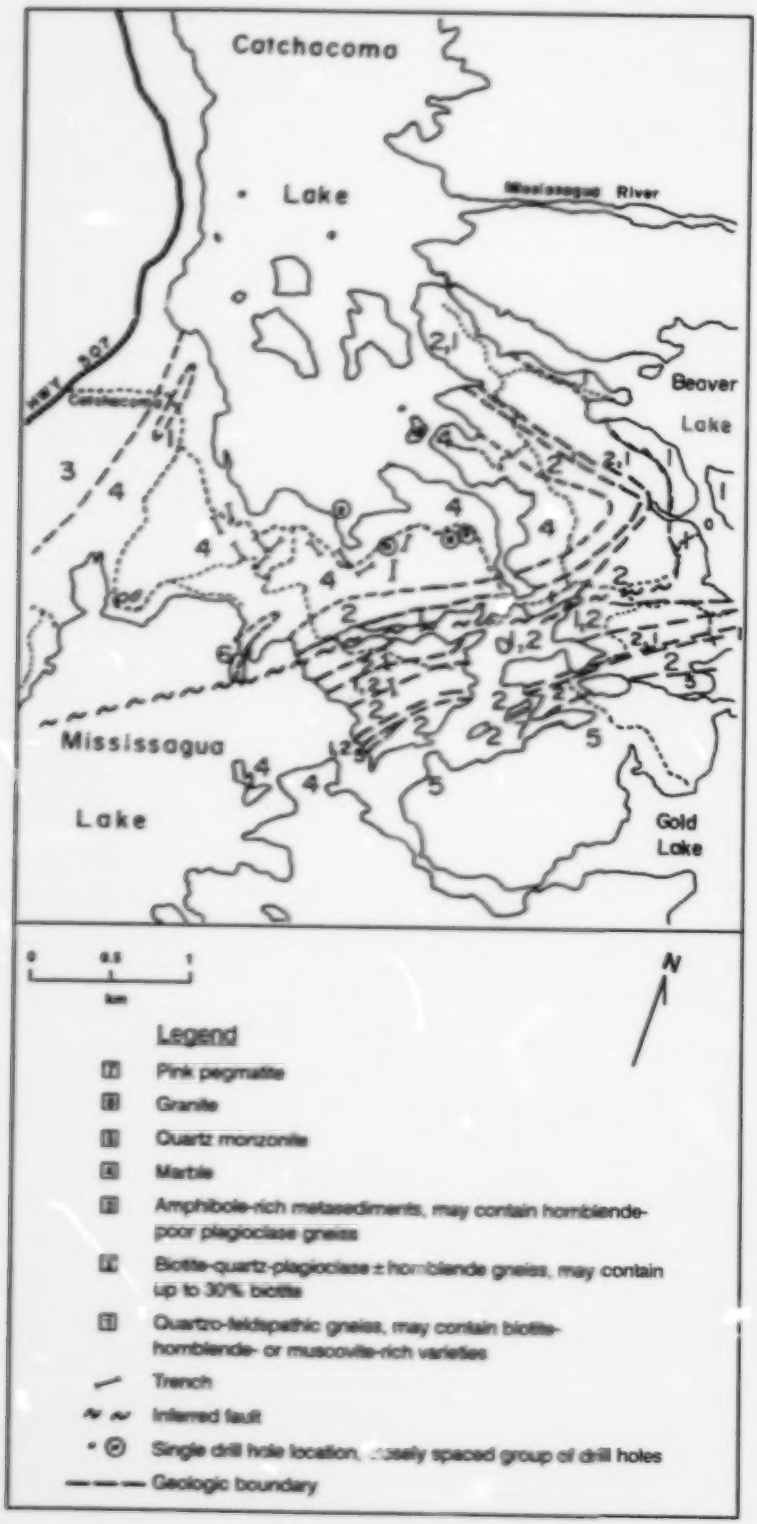

Figure B-2. Geology of the Goshawk Mines Limited property (*after* Bright 1981; Ontario Geological Survey 1983).

sists of four separate bodies over a strike length of 610 m (2000 ft.) in the central portion of the property. Zone C is located at the west end of the property and appears to be fairly good grade vermiculite (Archibald 1977b). Sufficient work was not conducted on Zones B and C to fully access them.

The concentration of vermiculite in bedrock is generally less than 5 percent, and decreases with depth.

Comments

Testing conducted by Goshawk Mines Limited has indicated that the vermiculite does not absorb water, i.e., it has low wettability; as a result, it is unsuitable for agricultural purposes. However, this quality is desirable for use in insulation, wallboard, plaster, and similar products which cannot tolerate moisture. Since the exfoliated material is fine-grained, it is suitable only for wallboard or plaster aggregate. The bulk density of the majority of the material is a little too high for current specifications, but should this problem be overcome the deposit is in a favourable location to compete for domestic markets.

Appendix C

OLYMPUS MINES LIMITED VERMICULITE PROPERTY

1969 Drilling Results
G.H.D. Consultants Limited, Toronto

HOLE NO.: W.E. 1
LOCATION: 100 feet NW of pit and 200 and SW of the NE end of the pit
STRIKE: S 45°E **DIP:** –45°
DATE DRILLED: September 16–19, 1969
PURPOSE: To test for vertical continuity below pit

FOOTAGE	DESCRIPTION	SAMPLE NO.	WIDTH (feet)
000–009	CASING		
009–072	METAMORPHIC PYROXENITE: broken & weathered		
72–078	DARK BASIC DIKE: light hematite staining in dike and walls		
78–124	METAMORPHIC PYROXENITE: massive, motley coloured grey–green with brown vermiculite flakes; low–grade vermiculite (± 5%); increase in vermiculite around 110 feet		
124–263	VERMICULITE–RICH METAMORPHIC PYROXENITE		
124–133		5401	9
133–143		5402	10
143–153	about 20% fine flakes of vermiculite	5403	10
153–161		5404	8
161–170		5405	9
170–180		5406	10
180–190	patchy, about 15% vermiculite	5407	10
190–200		5408	10
200–209		5409	9
209–219		5410	10
219–228		5411	9
228–237		5412	9
237–247		5413	9
247–256		5414	10
256–266	about 20%, uniform,	5415	9
266–276	fine–grained vermiculite	5416	10
276–285		5417	9
285–295		5418	10
295–305		5419	10
305–314		5420	9
314–323		5421	9
323–333		5422	10
333–342		5423	9
342–352		5424	10
352–362		5425	10
362–501	METAMORPHIC PYROXENITE – massive, green–grey, occasional short section showing up to 5% vermiculite		

END OF HOLE

HOLE NO.: W.E. 2

LOCATION: 100 feet NW of pit and 500 feet SW of the NE end of pit

STRIKE: S 45°E **DIP:** –45°

DATE DRILLED: September 20–23, 1969

PURPOSE: To test for vertical continuity beneath pit

FOOTAGE	DESCRIPTION	SAMPLE NO.	WIDTH (feet)
000–035	CASING		
035–070	METAMORPHIC PYROXENITE: vermiculite poor; generally light coloured, white–grey–cream–green; bands with estimated 5% vermiculite content; poorly banded, 60° to core axis		
070–093	METAMORPHIC PYROXENITE: pale green		
093–098	METAMORPHIC PYROXENITE: about 15% vermiculite, fine brown flakes		
098–107	METAMORPHIC PYROXENITE: white to dark grey		
101–160	METAMORPHIC PYROXENITE: massive, motley mixture of green, white and brown minerals—brown is vermiculite, green is pyroxenite, white is carbonate; about 5% low–grade vermiculite		
153–370	AS ABOVE: but increase in vermiculite appearing as seams, bands and patches; core lighter in colour		
153–160		5448	7
160–170	Light coloured, generally fine–	5426	10
170–180	grained vermiculite with patches	5427	10
180–190	of about 15% coarse vermiculite	5428	10
190–200		5429	10
200–210		5430	10
210–220	Light coloured, fine–grained	5431	10
220–230	vermiculite with patches of	5432	10
230–240	about 10% coarse vermiculite	5433	10
240–249		5434	9
249–259	Dark brown colours, crystalline;	5435	10
259–269	estimated 25% vermiculite but may	5436	10
269–278	be considerable mica present	5437	9
278–287		5438	9
287–296		5439	9
296–306	Light coloured, about 15% finely	5440	10
306–316	disseminated vermiculite	5441	10
316–325		5442	9
325–336		5443	9
336–345		5444	9
345–354		5445	9
354–364	Dark, patchy, about 10% vermiculite	5446	10
364–370			
370–425	METAMORPHIC PYROXENITE: massive, hard, motley green to white		
425	END OF HOLE		

HOLE NO.: W.E. 3
LOCATION: 50 feet NW of pit and 800 feet SW of NE end of pit
STRIKE: S 45°E **DIP:** 45°
DATE DRILLED: September 23–25, 1969
PURPOSE: To test for vertical continuity below pit

FOOTAGE	DESCRIPTION	SAMPLE NO.	WIDTH (feet)
000–038	CASING		
038–085	METAMORPHIC PYROXENITE: motley coloured brown, green and white vermiculite, to about 5%		
085–180	METAMORPHIC PYROXENITE: vermiculite rich		
085–095	Finely flaked, about 20% vermiculite	5449	10
095–105		5450	10
105–115		5451	10
115–125		5452	10
125–135	Patchy, lean and rich sections about 20% vermiculite	5453	10
135–145		5454	10
145–155	About 25% finely disseminated vermiculite	5455	10
155–165		5456	10
165–173		5457	8
173–180		5458	7
180–200	METAMORPHIC PYROXENITE: Motley coloured brown, green and white vermiculite; about 5% vermiculite		
200–230	METAMORPHIC PYROXENITE: vermiculite rich		
200–210	Patchy, some coarse material, about 15% vermiculite	5459	10
210–220		5460	10
220–230		5461	10
230–410	METAMORPHIC PYROXENITE: motley, coarse, massive, green, brown and grey coloured; little or no vermiculite		
410–440	METAMORPHIC PYROXENITE: light coloured, vermiculite poor, to about 5%		
440–455	METAMORPHIC PYROXENITE: light coloured, little or no vermiculite		
455	END OF HOLE		

HOLE NO.: W.E. 4
LOCATION: 550' N 45°E of Hole #1 at toe of stock pile
STRIKE: S 45°E **DIP:** 42°
DATE DRILLED: September 25–29, 1969
PURPOSE: To test the zone north easterly from pit

FOOTAGE	DESCRIPTION	SAMPLE NO.	WIDTH (feet)
000–023	CASING		
023–028	METAMORPHIC PYROXENITE: reddish rock with hematite		
028–090	METAMORPHIC PYROXENITE: motley, dark green to grey with stringers of carbonate and poor bedding @ 60° to core; occasional section of blue talcose rock; minor vermiculite developed around footage 95		
090–304	VERMICULITE-POOR METAMORPHIC PYROXENITE:		
090–095	Gradational change to light coloured, limy rock; motley appearance; often pearly grey to green with minor vermiculite and other micaeous minerals developed; vermiculite in patches & less than 5% in small flakes; narrow ribbon of dark talc		
270–304	Increase in vermiculite, but still about 5%		
304–313	BANDED VERMICULITE-RICH PYROXENITE: 15 to 20% vermiculite	5462	9
313–322	BANDED VERMICULITE-RICH PYROXENITE: 20 to 25% vermiculite	5463	9
322–323	TALC: blue-green colour		
323–341	BANDED VERMICULITE-RICH PYROXENITE: about 20%, banding at 60° to 80° to core axis		
323–332		5464	9
332–341		5465	9
341–351	BANDED VERMICULITE-RICH PYROXENITE: about 20% vermiculite	5466	10
351–372	BANDED VERMICULITE-RICH PYROXENITE: banding at ~70° to core		
351–361		5467	10
361–372		5468	11
372–383	BANDED VERMICULITE-RICH PYROXENITE: about 20% vermiculite	5469	11
383–392	BANDED VERMICULITE-RICH PYROXENITE: about 20% vermiculite, banding at 70° to core axis	5470	9
392–405	BANDED VERMICULITE-RICH PYROXENITE	5471	7
405–415	TALCOSE PYROXENITE: dark green with light green sections no vermiculite		
415–425	VERMICULITE-POOR METAMORPHIC PYROXENITE: about 15% vermiculite	5472	10
425–435	VERMICULITE-POOR METAMORPHIC PYROXENITE: about 15% vermiculite	5473	10
435	VERMICULITE-RICH METAMORPHIC PYROXENITE: about 20% vermiculite	5474	10
435–445	VERMICULITE-RICH METAMORPHIC PYROXENITE: about 20% vermiculite	5475	10
445–457	VERMICULITE-RICH METAMORPHIC PYROXENITE: about 20% vermiculite	5476	12
457–471	DARK PYROXENITE: with limy bands. may include altered basic dike		
471–478	BANDED VERMICULITE-RICH METAMORPHIC PYROXENITE: about 15% vermiculite		
478–488	BANDED VERMICULITE BEARING METAMORPHIC PYROXENITE: alternating vermiculite-rich and vermiculite-poor bands; about 15% vermiculite		
488–496	BANDED VERMICULITE-RICH METAMORPHIC PYROXENITE: about 15% vermiculite		
496–515	METAMORPHIC PYROXENITE: green to black, without vermiculite except		
501–505	Vermiculite-rich zone, about 25% vermiculite		
515	END OF HOLE		

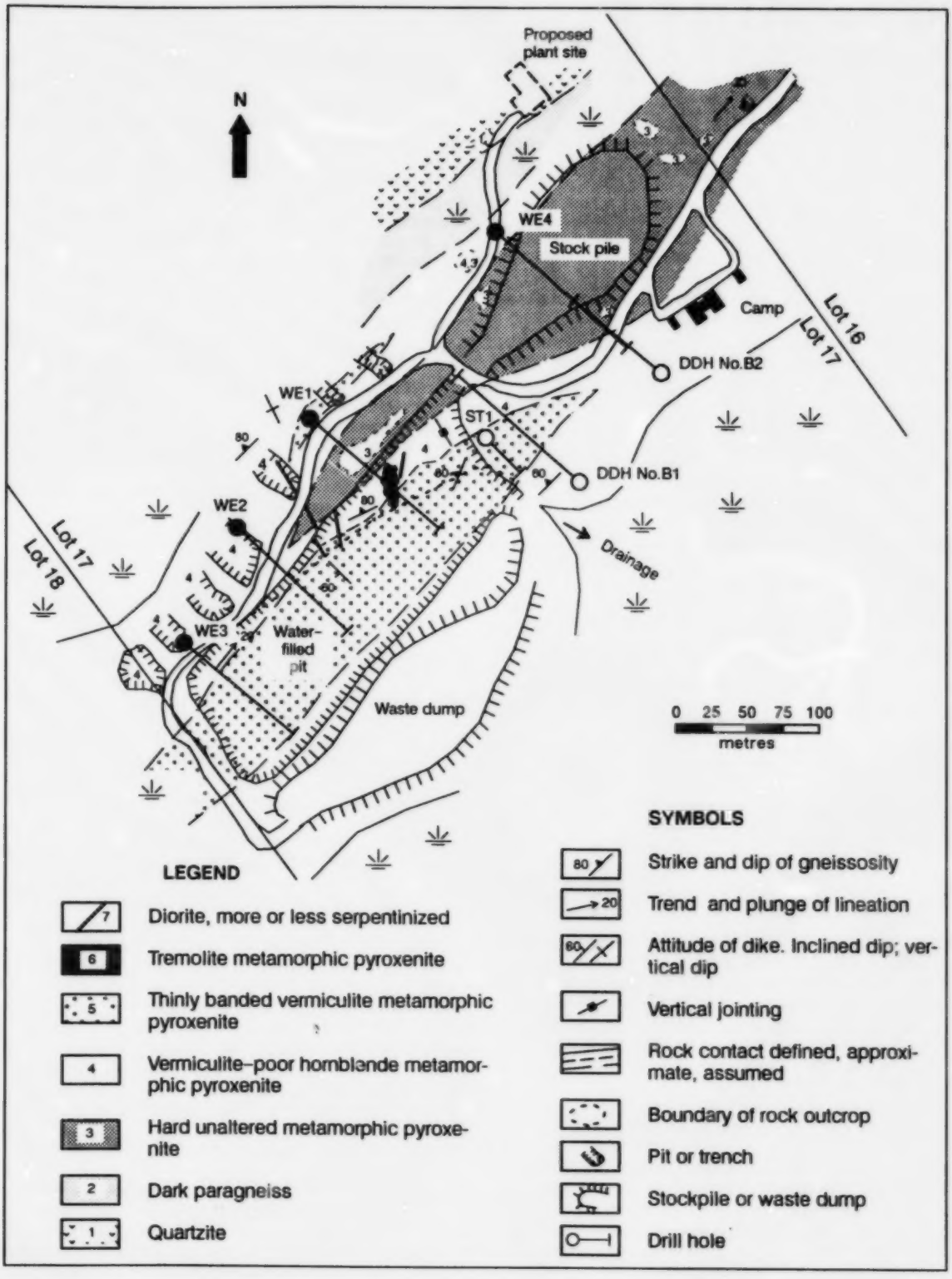

Figure C-1. Drill hole location map, Olympus Mines Limited property (*after* Cunningham 1969; Guillet 1962).

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CONVERSION FACTORS FOR MEASUREMENTS IN ONTARIO GEOLOGICAL SURVEY PUBLICATIONS

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
		LENGTH			
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709 7	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
		AREA			
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
		VOLUME			
1 cm^3	0.061 02	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.308 0	cubic yards	1 cubic yard	0.764 555	m^3
		CAPACITY			
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
		MASS			
1 g	0.035 273 96	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 75	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 62	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 908 8**	t
		CONCENTRATION			
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.

MAPS
NOT
FILMED

CARTES
OMISES